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THE LARGE QUARTZ VEINS OF GREAT BEAR LAKE, CANADA.[1]

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INTRODUCTION.

QUARTZ veins of unusual size are widely distributed throughout the area lying east of Great Bear Lake to the Coppermine River, and south as far, at least, as Hottah Lake, in the Northwest Territories, Canada. The large veins attain maximum widths, including stockworks, up to one thousand feet, and have been traced, as continuously as could be expected from the nature of the country and the unexplored character of much of it, along their strike for distances up to fifty miles, and are reported to extend further.

It is the purpose of this paper to present the results of a study of the wall-rock alteration along one of these large quartz veins, with notes on its mineralogy. The general occurrence and distribution of the veins are reviewed and some conclusions drawn as to their origin. The opportunity to collect specimens and data for this work was provided by the Geological Survey of Canada during the field season of 1932, when the writer acted as assistant to Dr. D. F. Kidd in this area.

The writer wishes to express his thanks to Dr. Kidd for suggesting the problem; to the Geological Survey of Canada for the loan of notes and specimens collected; to Dr. F. T. Jolliffe for data, specimens and photographs of the "Sloan Dyke" at the Quartz Island locality; and to Professor E. L. Bruce, Queen's

[1] Published with the permission of the Director of the Geological Survey of Canada.

University, under whom this work was carried out, for advice and assistance. Professor W. H. Newhouse, Massachusetts Institute of Technology, offered helpful advice in preparing this paper for publication.

GENERAL GEOLOGY OF THE AREA EAST OF GREAT BEAR LAKE.

The area on the east side of Great Bear Lake is underlain by rocks, some undoubtedly of Pre-Cambrian age, and others possibly late Pre-Cambrian. The general geology may be briefly summarized in the following table of formations.[2]

Quaternary	Silt, clay, gravel, morainal material.
	——— Unconformity ———
Pre-Cambrian (?)	Basic dikes and sills; large quartz veins.
	—— Intrusive contact ——
	Little disturbed sandstone, quartzite, and conglomerate (Hornby Bay Series).
	——— Unconformity (?) ———
Pre-Cambrian	Granite and other acid plutonic rocks.
	—— Intrusive contact ——
	Quartz mica diorite and granodiorite.
	—— Intrusive contact (?) ——
	Sedimentary and volcanic complex,—
	(*a*) Cameron Bay Group—conglomerate, tuff, argillite, etc.
	(*b*) Echo Bay Group—porphyritic volcanics, tuff, argillite, quartzite, conglomerate, etc.

The distribution of these rocks is shown on Map 296 A, Geological Survey of Canada, 1933. The granites vary from place to place in composition and texture and may not all be of one age. Evidence for the presence of granites of at least two ages has been found.[3]

No pegmatite dikes have been found in the area. Aplite dikes older than the large quartz veins are present. Some of the

[2] Kidd, D. F.: Great Bear Lake Area. Geol. Survey of Canada, Summ. Rept., 1932, pt. C, p. 4.

[3] *Idem*, p. 11.

Furnival, G. M.: Silver mineralization at Great Bear Lake. Can. Min. Jour., vol. 55, p. 5, 1934.

granites are bordered by granophyres and fine-grained porphyritic facies.

The formations of the Old Complex have been folded into northwest-trending folds with dips that seldom exceed forty-five degrees. The Hornby Bay Series is gently tilted, with dips of less than ten degrees.

FIG. 1. The "Sloan Dike" northeast of Hunter Bay, Great Bear Lake, looking east. Hunter Bay settlement and airplane base in center. "Sloan Dike," in background, outcrops as a long white ridge, over five hundred feet above the lake level. (Courtesy of Royal Canadian Air Force).

Most of the faults in the area have a general northeastward trend and the northwest sides have apparently moved northeastward. Many of the large quartz veins occupy faults that cut all the older rocks. Some of the faults have been traced for distances of approximately eighty miles. There are also other faults of a north-south trend, some of which include basic dikes up to forty miles or more in length.[4]

[4] Kidd, D. F.: *Op. cit.*, p. 18.

GENERAL FEATURES OF THE LARGE QUARTZ VEINS.

Locally, the large quartz veins are prominent topographic features. They rise as great white ridges (Fig. 2) that stand out as striking landmarks. A large quartz vein, which at one place outcrops as a prominent ridge, may in contrast be found farther along its strike in partially drift-filled depressions.

FIG. 2. The "Labine Dike," 2½ miles NE of Hunter Bay, Great Bear Lake, looking north. The "Dike" here is a prominent ridge three-quarters of a mile long. (Courtesy of Royal Canadian Air Force.)

The distribution of thirty-six large quartz veins is shown on map 296 A. More doubtless occur here, and in addition, others are known to occur as far south as Hottah Lake and east as far at least as Red Rock Lake. The large quartz vein on Red Rock Lake has been traced for a distance of seventeen miles. It varies in width up to three hundred feet.[5]

A belt of seven large quartz veins occurs in the Camsell River area, one of which is over five hundred feet wide. Another oc-

[5] McLaren, D.: Personal communication, 1933.

curs on Clut Island in Lac Clut, and there are several on the east shore of Hottah Lake.

The large quartz veins strike northeasterly and have steep dips. Four of these veins are known to occur in faults of considerable magnitude. Along two of these faults there is an apparent horizontal displacement of the order of four miles. Shearing is evident along these faults.

In addition to the large quartz veins there are also innumerable smaller veins of similar trend. Seven basic dikes have been noted which parallel the large quartz veins.[6] This is probably due to parallel zones of weakness which, therefore, must have persisted for some time.

The veins generally consist of two parts; the main part is composed principally of quartz with minor amounts of vein breccia; this is flanked by stockworks of quartz stringers on one or both sides.

Minerals other than quartz are sparse. They are specularite, bornite, chalcopyrite, covellite, chalcocite, pyrite, famatinite, and siderite. Recently, pitchblende has been found in one of the large quartz veins on Hottah Lake. These minerals represent last-stage depositions.

The large quartz veins cut indiscriminately through the various rocks of the area. Two of them have been found cutting the Hornby Bay series, and therefore the veins are considered younger than these rocks.

THE "SLOAN DIKE."

A large quartz vein, locally called the "Sloan Dike," outcrops on Quartz Island, just north of Labine Point, and has been traced for a distance of at least fifty miles to the northeast (Fig. 1). At Hunter Bay another large vein, called the "Labine Dike," diverges from it (Fig. 2).

The "Sloan Dike" varies in strike from N. 30° E. to N. 60° E., dips steeply, and ranges in width up to three hundred feet.

[6] Riley, C.: Some Mineral Relations in the Great Bear Lake Area. Can. Min. Jour., vol. 54, no. 4, p. 141, 1933.

It lies in a fault with an apparent horizontal displacement of about four miles, and cuts indiscriminately through metamorphosed volcanics and sediments of the Old Complex, granodiorite, and granite. The vein in general consists of two parts; a more massive portion composed mostly of vein quartz, and stockworks of smaller quartz veins and stringers. Those nearest the margin of the vein occur at angles which suggest that fracturing developed at the time of the major faulting. Vein breccias are common and are composed of angular fragments, up to several feet in diameter, of several rock types that have undergone alteration. These vein breccias have also been fractured and recemented by later quartz. Vugs and druses lined with quartz, and in some places specularite, are common.

MINERALOGY.

Quartz.—The "Sloan Dike" is composed almost entirely of quartz. The quartz is of two main types, one massive, the other banded. The banded type consists of alternate bands, of milky and of transparent colorless quartz, varying in size from those which are extremely narrow up to those one-quarter of an inch or more wide, and except in cases of zoning in a single crystal, the streaks are generally finely crenulated (Fig. 4). The banding is not always parallel to the walls of the vein but may be quite irregular; in places the bands follow peculiar angular patterns and inclose earlier quartz, and rock fragments.

The microscope reveals that the banding of the quartz is due to the distribution of inclusions; the clear bands are relatively free of inclusions, but the milky bands are packed with an infinite number. Some of the inclusions are liquid but many are minute particles of solid matter. These are not all of the same mineral, since the refractive indices, color, and shape vary considerably. Tiny shreds of what appear to be a micaceous mineral were noted. The quartz in which the banding occurs is coarse-grained and of the anomalous variety that Adams[7] calls feather quartz. The

[7] Adams, S. F.: A Microscopic Study of Vein Quartz. ECON. GEOL., vol. 15, p. 628, 1920.

inclusions are arranged in irregular parallel rows transverse to the vertical axes of the quartz feathers (Figs. 4–6). The rows of inclusions do not occur at the base or tip of the quartz feathers but part-way down a single feather which is optically continuous from one side of the band to the other. The ordered arrange-

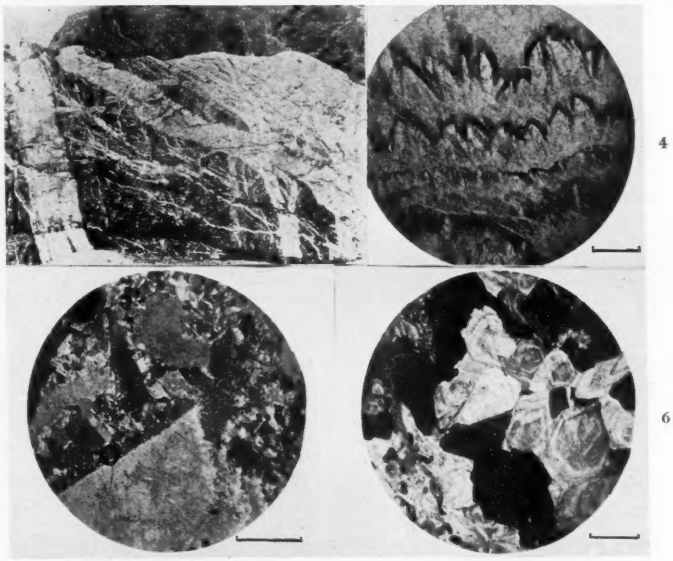

FIG. 3. Vein breccia and banded quartz on small quartz island north of Labine Point. Three ages of quartz can be recognized at right hand side. (Photograph by F. T. Jolliffe.) × 1/10.

FIG. 4. Banded quartz from NE corner of the small quartz island. The roughly parallel dark bands are bands of inclusions, which in the hand specimen appear as finely crenulated milky white bands. Thin section; black line = 1 mm.

FIG. 5. Massive quartz, Quartz Island, with typical lack of uniformity of texture. At right hand side is a feathered crystal of quartz with a clear core. X-nicols; black line = one-half mm.

FIG. 6. Country rock thirty-five feet from the margin of the "Sloan Dike" at Hunter Bay, showing zonal arrangement of inclusions in quartz veinlets that transect the country rock. X-nicols; black line = 1 mm.

ment of the inclusions indicates a relation to the crystal structure of the quartz. Possibly they represent breaks in deposition. The feathered quartz commonly occurs around masses of chalcedonic quartz and extends out from it. Patches and shreds of chloritic and sericitic material are present in sufficient amounts to give the chalcedonic quartz a pale greenish color in transmitted light. Dentated boundaries around the large quartz grains indicate a certain amount of rearrangement. A chemical analysis of this banded quartz yielded 1.83 per cent. Al_2O_3.

The patches and shreds of sericite and chloritic material that occur in the chalcedonic quartz may probably be the unreplaced remnants of altered and silicified country rock.

The massive quartz is a medium- to coarse-granular milky variety. It contains some irregular patches, up to one centimeter across, of a finely divided kaolin mineral in which fragments of unaltered plagioclase are recognizable. Under the microscope the most notable feature of the quartz is the complete lack of uniformity in texture (Fig. 5). Angular masses of quartz up to ten millimeters in diameter occur in a chalcedonic matrix. These masses are regarded as fragments of quartz grains, since each mass is optically continuous throughout and straight bands of inclusions crossing one portion of a mass are sharply terminated at the margin of the mass (Fig. 5). The inclusions are both liquid and solids of various minerals too small for identification. Euhedral crystals of quartz up to four millimeters in diameter are found in this massive quartz. Some of these show simple and regular twinning, with the c-axis as the twinning axis and the twinning plane parallel to a prism face. Large grains of quartz with dentated borders suggest that some grains may have formed as the result of replacement by partial rearrangement. Chalcedonic quartz is abundant, commonly completely surrounding many of the larger fragments of quartz, and at places indenting them. The chalcedonic quartz contains a considerable amount of chloritic and sericitic material, specks of hematite, and other incompletely replaced material distributed through it, so that the color in trans-

mitted light is very pale green. Small patches and shreds of incompletely replaced silicates are scattered through most sections of the massive quartz, although they are not perceptible in the hand specimen.

Many of the anomalous forms of feathered quartz described by Adams are present in sections of both the massive and the banded quartz.

The walls of druses are lined with crystals of quartz up to an inch long, many of which are zoned. The tips of the crystals in many of the vugs are coated with quartz containing much finely divided hematite.

As many as three distinct periods of quartz deposition are recognizable by the cross-cutting relations of stringers that make up the veins (Fig. 3). Each period has been preceded by a period of readjustment along the fractured zone. The finely banded quartz occurs along fractures that have developed late in the history of the veins. It commonly fills fractures in the massive quartz of the main part of the vein. The early quartz, therefore, is generally massive, and the later quartz is banded.

Specular Hematite.—Following the third period of quartz deposition, a readjustment in the vein in the vicinity of Quartz Island resulted in local brecciation and the development of cross fractures, in which a large amount of specular hematite with some quartz was deposited. The hematite occurs in a colloform habit which may indicate colloidal deposition.

Fragments of granite included in the vein were studied microscopically. It was found that the feldspar and hornblende had altered to a mass of secondary products, largely sericite and chlorite; these were subsequently more or less replaced by chalcedonic quartz, and finally large amounts of finely divided hematite were introduced into the partially altered and replaced fragments.

Copper Sulphides.—Late readjustments along the quartz vein resulted in the development of a sheared zone within and parallel to the margin of the vein at Hunter Bay. In this sheared zone were deposited chalcopyrite, bornite and chalcocite, with minor amounts of famatinite, pyrite, hematite and siderite.

Wall Rock Alteration.

The "Sloan Dike" outcrops continuously for a distance of seven miles at Hunter Bay. Here the alteration of the wall rocks is best exhibited. Just northeast of the copper deposits the vein cuts granodiorite and a metamorphosed volcanic flow rock of the Old Complex. The vein here varies from one hundred and twenty-five feet up to two hundred feet in width, with stockworks extending up to fifty feet from the margin. Wall-rock alteration extends up to distances of seventy-five feet from the margin of the main part of the vein.

Specimens for detailed study were selected from two localities where the vein cuts granodiorite, one a half mile northeast of Hunter Bay and the other about one and a half miles northeast of the Bay.

Mineral Change.—A series of nineteen specimens were taken at the point a mile and a half northeast of Hunter Bay, over a distance of sixty-five feet from the margin of the vein southeast towards the relatively fresh granodiorite. They indicate a decided, although irregular, increase in the degree of alteration and amount of replacement by quartz toward the vein.

Fragments of slightly altered material were found close to the vein, whereas other material at the same distance had been considerably altered. This may be due to local protection by early quartz. In places there is a notable although slight increase, in the basicity of the altered granodiorite, expressed by relatively larger amounts of dark colored minerals. The orthoclase here is still quite fresh-looking although of a deeper red color, and crystal outlines are distinct; the rock is somewhat finer grained. It seems likely that these variations are original. Owing to this lack of regularity in the alteration only a determination of its general trend will be attempted.

The granodiorite is a medium-grained massive rock, consisting of light brown to salmon to white feldspar, glassy quartz, and hornblende. Specimens selected from both localities at distances of over one hundred feet from the margin of the vein showed the composition of the granodiorite to be about forty-five to fifty

per cent. oligoclase of the composition Ab_{85} An_{15} in well formed crystals, twenty per cent. quartz, sixteen to twenty per cent. orthoclase, about ten per cent. idiomorphic green hornblende, with some magnetite and apatite. The rock is not fresh. The orthoclase is altered to kaolin, and the interiors of the subhedral oligoclase crystals, to a mass of finely divided secondary white micas with some zoisite and quartz; the hornblende, to chlorite, calcite, epidote, and magnetite; some leucoxene was noted. The skeletal outlines of idiomorphic hornblende crystals inclose unaltered hornblende surrounded by alteration products. The quartz is severely fractured. Magnetite is both a primary constituent and secondary after hornblende. Apatite is present as small lath-shaped crystals.

At sixty-five feet from the margin of the vein this rock is seamed by tiny veinlets of quartz up to one-eight inch wide. This rock ranges through the basic types referred to, into one consisting of waxy-looking, salmon-pink feldspar, and a large amount of lusterless light-green feldspar, milky white quartz, and a dark green ferromagnesian mineral, the whole cut by numerous seams of quartz. This persists to within six feet of the vein. From that point on, there is a rather rapid transition to a bleached fine-grained mixture of light pink to light green lusterless material, with irregular patches of a pale green material. Mineralogical changes through the nineteen specimens will be summarized briefly.

The orthoclase alters to a kaolin mineral and sericite and is replaced by chalcedonic quartz. All stages in the replacement may be observed. Initial stages take place along cleavage planes and around the margins of the grains. The oligoclase alters first to a mass of finely divided secondary products, in large part sericite. This material in turn is replaced by chalcedonic quartz. The completely altered oligoclase may retain its crystal outline until replacement by the chalcedonic quartz occurs.

Hornblende alters to chlorite (much of which is penninite), calcite, quartz and magnetite. A few crystals of rutile occur in the chlorite. These alteration products tend to retain the crystal

outlines of the idiomorphic crystals of hornblende until they are replaced in turn by chalcedonic quartz.

At six feet from the margin of the main part of the vein, all crystal outlines have been destroyed and in thin section the rock is found to consist of eighty-five per cent. quartz, mostly chalcedonic. A few incompletely replaced crystals of orthoclase are left, and patches and shreds of a pale green chlorite, flakes of sericite and scattered patches of hematite make up the rock. From here to the margin of the vein the main change is increase in the amount of chalcedonic quartz at the expense of remnants of former minerals.

Seams and stringers of quartz transecting this altered wall rock commonly show a zonal arrangement of solid, with some liquid, inclusions in a relatively coarse comb or feather quartz (Fig. 6).

Hematite is generally present, in some cases as relatively large patches, in the highly altered wall rock immediately adjoining the vein.

The wall-rock alteration was also studied at the locality about a half mile to the northeast of Hunter Bay. Specimens were selected from the granodiorite lying northwest of the vein. The vein is bordered here on the northwest by a stockwork up to thirty-five feet wide. The mineralogical changes are essentially the same as those described above.

Southeast of the vein at this point is a chocolate-brown porphyritic flow rock with phenocrysts of oligoclase of composition Ab_{75} An_{25}, in an aphanitic groundmass containing much finely divided hematite. The oligoclase is altered to sericite. The groundmass appears to be made up of finely divided feldspar, quartz, epidote, mica, with some magnetite and calcite. Approaching the margin of the vein the oligoclase is completely altered to sericite, quartz makes up a large proportion of the groundmass, and hematite is less abundant. At the margin of the vein, the rock is bleached in color and is composed largely of chalcedonic quartz, with irregular patches of incompletely replaced material and some fairly large patches of hematite.

A fragment of a chocolate-brown, fine-grained, cherty quartz porphyry taken from the vein itself was found to be composed entirely of chalcedonic quartz and finely divided hematite. The quartz eyes themselves are composed of chalcedonic quartz. The rock, whatever its original composition, has undergone complete silicification.

Summary of Mineral Change.—Even the freshest-looking granodiorite of the localities studied is considerably altered. This alteration, as noted by Riley,[8] is a feature common to the various granite masses of the district, and therefore may be regarded as a regional metamorphism. But as the margin of the vein is approached, there is a local alteration of the feldspars to secondary minerals, largely sericite; and of the ferromagnesian minerals, largely to chlorite and penninite, together with calcite, quartz and magnetite. The changes become progressively more complete and are followed by replacement of both original and secondary minerals by chalcedonic quartz and by the introduction of vein quartz in veinlets.

The alteration therefore is (a) hydration during which sericitization and chloritization take place, and (b) replacement by silica.

Hematite occurs in the altered granodiorite and the altered porphyritic volcanic rock at the margin of the vein. In view of this it is difficult to explain the bleaching of the porphyry from chocolate-brown to pale greenish-white near the vein.

Chemical Change During Alteration.—Chemical analyses were made of specimens of the altered and "fresh" granodiorite, selected from the first locality studied, to determine the chemical changes brought about in the wall rocks by the vein-forming agents. A specimen of the "fresh" granodiorite was selected at a distance of about one hundred feet from the vein, and of altered granodiorite at a distance of about one foot from the margin of the vein. The results of the two analyses are shown in Table I, together with a comparison based upon the assumption that the volume remained constant during the wall-rock alteration. The changes are shown graphically in Fig. 7.

[8] Riley, C.: *Op. cit.*, p. 138.

TABLE I.

CHEMICAL CHANGE DURING ALTERATION.

	No. 1	No. 2	3	No. 4	No. 5	No. 6	No. 7
SiO_2.....	55.72%	71.79%	69.59%	13.87+		24.89+	
Al_2O_3....	17.72	13.53	13.11		4.61−		26.01−
Fe_2O_3....	.36	2.47	2.39	2.03+		563.90+	
FeO.....	2.30	.78	.76		1.54−		66.95−
MgO....	5.33	2.41	2.34		2.99−		56.10−
CaO.....	2.26	1.03	1.00		1.26−		55.75−
Na_2O....	7.88	3.32	3.22		4.44−		56.34−
K_2O.....	3.17	1.20	1.16		2.01−		63.41−
H_2O+...	1.59	3.24	3.14	1.55+		99.75+	
H_2O-...	.12	.12	.12				
TiO_2.....	.83	.28	.27		.56−		67.47−
P_2O_5.....	.57	.43	.42		.15−		26.32−
MnO....	.44	.05	.05		.39−		88.63−
CO_2.....	.91	.45	.44		.47−		51.65−
	99.20%	101.10%					

No. 1 Analysis of "fresh granodiorite," specific gravity = 2.869; No. 2. Analysis of altered granodiorite, specific gravity = 2.781; No. 3. Percentages in No. 2 multiplied by the factor 2.781/2.869 to reduce to common volume; Nos. 4 and 5. Gains and losses in oxides; Nos. 6 and 7. Percentage gains and losses in oxides.

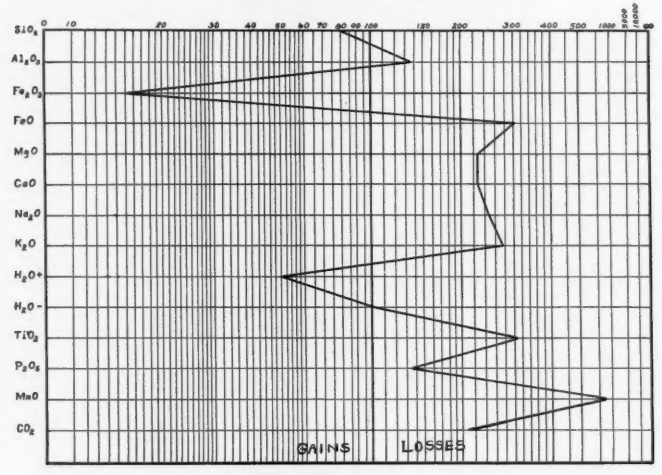

FIG. 7. Straight line diagram showing gains and losses of oxides caused by hydrothermal alteration of the wall rock along the "Sloan Dike" at Hunter Bay.

It was considered unnecessary to calculate the mineral change during alteration by recasting the analyses into mineral percentages, since the " fresh " granodiorite actually is considerably altered.

On the assumption of constancy of volume these analyses show that all the oxides except silica, ferric oxide, and combined water, have been removed during the alteration of the granodiorite by the vein-forming agents. Silica has probably been introduced entirely as quartz, ferric oxide mainly as hematite, and water is combined in the secondary micas.

It should be noted here that the actual percentage of quartz which has been introduced into the wall rock is much larger than that indicated in the analyses. The analysis of the altered rock does not take into account the large amount of silica which is present as stringers in the rock at this point.

GENESIS.

The evidence points to a long continued process of deformation and depositions of silica. The succession has not been worked out in detail, but there are at least four periods of deformation, three of which have each been followed by a period of abundant quartz deposition. The first period of deformation represented a major regional deformation. This was followed by minor adjustment of stresses along the vein. The early quartz is in general massive, milky white, and of extremely irregular grain size. It contains remnants of incompletely replaced silicates. Quartz of later periods commonly shows a banded structure. The last stage of abundant quartz deposition was accompanied by deposition of specular hematite. Local shearing, parallel to the margin of the vein, in places contains later bornite, chalcocite, chalcopyrite, famatinite, pyrite, hematite and siderite.

The introduction of the quartz in the veins has been accompanied by extensive alteration of the wall rocks. This alteration consists of sericitization and chloritization to a small extent. It is followed by replacement by silica and the introduction of hematite. Veinlets of later quartz commonly traverse the altered and replaced wall rock, indicating that the replacement of the wall

rock by quartz was an early process in the history of the formation of these large quartz veins.

It seems probable that the remarkable widths of the veins are due to the existence of a wide zone of severely fractured rocks, which permitted easy circulation of the silica-bearing solutions and resulted in the complete replacement of a considerable part of the zone. Brecciation of this early formed vein-filling was then followed by the deposition of the later stages of banded quartz along open fissures.

The nature of the solutions cannot be definitely inferred. Colloform structures are present in the quartz and the associated hematite. But until such time as the existence of colloidal solutions under elevated temperatures and in complex systems has been demonstrated, one is perhaps unjustified in stating that colloidal solutions were present during the formation of these veins. The simple, regular twinning present in the euhedral quartz grains of the massive type of quartz characterizes low-temperature quartz. In quartz which has inverted, the twinning is irregular in small patches, bearing no relation to external form.[9] This evidence indicates, therefore, that some of the earliest formed quartz was deposited at temperatures below 575° C. It would appear, then, that the solutions were hydrothermal and not of very high temperature.

The areal distribution and so enormous a volume of silica as that contained in these veins indicate that the source of supply must have been a magma corresponding to an acidic rock such as granite and a magma reservoir of large size. There are granites of at least two different ages in the area, but neither of them has as yet been found in contact with the Hornby Bay series, so that their relations to the quartz veins are undetermined. However, it may be significant that the younger granite is a coarse-grained quartzose variety of batholithic dimensions, and that local disseminations and veins of hematite occur within it.

The absence of pegmatites in the area has been commented upon. It is improbable that the occurrence of these tremendous quartz veins and the lack of pegmatites is a mere coincidence.

[9] Winchell, A. N.: Elements of Optical Mineralogy, Pt. II, 3d ed., p. 56, 1933.

CONCLUSIONS.

The large quartz veins of Great Bear Lake have been formed by the deposition of quartz from hydrothermal solutions at not very elevated temperatures. These solutions have been introduced into and have passed upward along faults of great persistence and displacement, along which the rocks were severely fractured over widths up to a thousand feet. The faults were formed as the result of some regional stress or stresses of unknown origin. The age of the faults and accompanying quartz veins is not definitely known, but they are later than the Hornby Bay series.

Extensive alteration and replacement of the severely fractured wall rocks by silica accompanied the formation of the veins. Evidence indicates that the remarkable width of the veins is probably due to the existence of wide zones of severely fractured rocks, and their replacement in large part by silica-bearing solutions.

Additional information is necessary before the genetic relations of the veins can be determined with certainty.

The large quartz veins of Great Bear Lake are similar in many respects to the "huge mass of quartz" at Lantern Hill, Connecticut, as described by Gregory [10]; to the Bohemian Pfahl, the Great Pfahl and other large quartz veins of the Hercynian massifs of Central Europe, as described by Suess [11]; and to the "Great Sulphur Vein" of the Pennines, England, as described by Thompson.[12]

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May 6, 1935.

[10] Rice, W. N. and Gregory, H. E.: Manual of the Geology of Connecticut. Conn. Geol. and Nat. Hist. Survey. Bull. 6, p. 136, 1906.

[11] Suess, E.: The Face of the Earth. Vol. 1, pp. 204–209, and vol. 4, p. 49. 1904.

[12] Thompson, L. M.: The Great Sulphur Vein of Alston Moor. Proc. Univ. of Durham Phil. Soc., vol. IX., pt. 2, pp. 91–98, 1934.

OIL POSSIBILITIES IN NORTHWEST DISTRICT, WESTERN AUSTRALIA.

D. DALE CONDIT.[1]

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INTRODUCTION.

IN THIS paper is described an area of sedimentary rocks in the Northwest District of Western Australia, known geologically as the Northwest Basin, the area of which is approximately 36,000 square miles. Publications of the State Geological Survey contain many references to the geology, among the more important of which are those of A. Gibb Maitland, former Government Geologist; but the area really has received very little detailed attention either on the part of the State Survey or visiting geologists. For instance, certain isolated portions were examined for the first time in 1923 by F. G. Clapp, in the course of his studies as to oil possibilities in this and other sedimentary basins of Western Australia. His several published papers set forth par-

[1] Published through the courtesy of the Managing Director of Oil Search, Limited, Sydney, Australia.

ticulars of interest, and he took an unfavorable attitude as to oil possibilities.[2] Dr. Woolnough, Geological Advisor to the Commonwealth Government, during his extensive aerial survey operations in various parts of Australia, made important observations as to this area.[3]

During the past year, the author, assisted by E. A. Rudd, made a reconnaissance trip of several weeks over the Northwest Basin, which led to a realization that the scant published data give an imperfect and misleading picture regarding the geology. Several years previously, structural and stratigraphic studies had been carried on in the Wooramel River area by Rudd and others. The reconnaissance trip by the author resulted in the planning of broad stratigraphic studies which subsequently have been carried on by H. G. Raggatt. Results now in hand differ widely from those of Clapp in ways vitally affecting the problem as to oil possibilities. The accompanying geological sketch map, Fig. 1, has been compiled from the recent mapping. The essential features of the geology are described briefly in the following pages.

GEOGRAPHIC AND GEOLOGIC SETTING.

The Northwest Basin is composed of Permo-Carboniferous, Mesozoic and Tertiary rocks occupying a length of 400 miles along the coast from north to south, extending from the 22nd to the 28th degree of south latitude, and a width from east to west of 100 to 175 miles. The adjacent country consists of a pre-Cambrian complex which forms most of the vast interior region, but several hundred miles to the northeast is a much larger area of sedimentary rocks—the Desert Basin—extending far into the interior. To the south is yet another such area known as the Coastal Plain Basin.

[2] Clapp, F. G.: A Few Observations on the Geology and Geography of the Northwest and Desert Basins, Western Australia. Proc. Linnean Soc., New South Wales, vol. 1, pt. 2, pp. 47–66, 1925; The Oil Problem in Western Australia. Econ. Geol., vol. 21, pp. 409–430, 1926; Oil Prospects of the Northwest Basin of Western Australia. Amer. Assoc. Petr. Geol., vol. 10, no. 11, pp. 1137–1149, 1926.

[3] Woolnough, W. G.: Report on Aerial Survey Operations in Australia during 1932. Commonwealth of Australia, 1933.

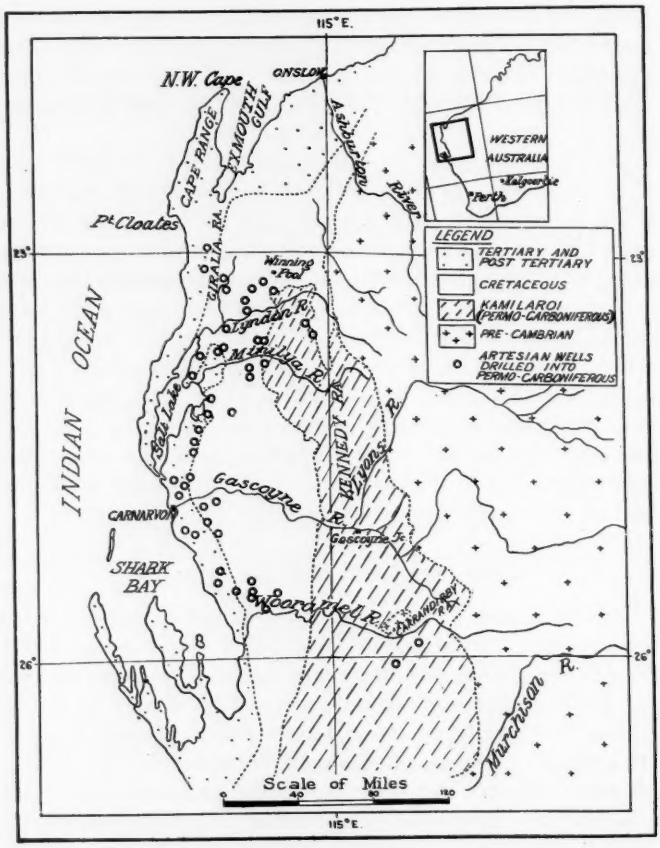

FIG. 1. Geologic sketch map showing all but southernmost part of Northwest Basin.

Over most of the interior crystalline-rock region adjacent to the Northwest Basin, elevations exceed 1,000 feet, and there are occasional hill ranges considerably higher. In the eastern part of the basin are discontinuous hill ranges composed of strike ridges of the more resistant sandstone and limestone formations

of the Permo-Carboniferous. Dips here, mostly basinward, commonly range from a few degrees to 10 degrees, and erosion of the variably resistant portions of the tilted strata has given rise to the Kennedy Range, approximately 1,000 feet in elevation and 65 miles in length, extending from the Minilya to the Gascoyne River. The broad summit is a slope of beds dipping gently westward, and the eastern escarpment presents a practically continuous precipitous front. Another range to the south near the Wooramel River, the Carrandibby, formerly reported as composed of Permo-Carboniferous rocks, is pre-Cambrian. Most of the surface westward from the Permo-Carboniferous outcrop is a gently-sloping, slightly dissected plain composed of Mesozoic strata of almost imperceptible westward dip. Easternmost fringes are locally eroded into isolated mesas and buttes such as are strikingly in evidence southeastward from Winning Pool. Nearer the coast is a strip of Tertiary and post-Tertiary limestones, uplifted beach deposits and wind-blown sands, the relief throughout being slight, with the exception of the northern portion adjacent to Exmouth Gulf, where folded late-Tertiary strata compose the mountainous Cape Range, 1,200 feet or more in elevation.

The rainfall, although somewhat erratic, averages from as little as 4 inches in some parts to as much as 10 inches in others, being sufficient in most years to provide fair grazing conditions. Most of the region is good sheep country and is portioned into numerous large holdings known as "stations." Artesian conditions prevail over much of the coastal plains, and brackish water suitable for stock is obtained by drilling.

The history of structural deformation over much of Australia, and particularly the western portion, has been comparatively uneventful since pre-Cambrian time. Most of the mild deformation in evidence took place shortly after the close of the Paleozoic, as illustrated by gentle folding and local faulting in the Permo-Carboniferous beds interrupting the regional westward dips. During extensive erosional planation after the close of the Paleozoic these sedimentary rocks were entirely removed over areas of uplift, and it is surmised that the several basin remnants may be parts of formerly continuous deposits laid down in embayments

of a common sea. With resubmergence in late Jurassic or early Cretaceous time came transgressive deposition of siliceous, silty and shaly sediments laid down nonconformably on all older formations. The horizons represented include both Lower and Upper Cretaceous. Tertiary deposition took place in a shallow, less extensive sea, with calcareous deposits representing Eocene, Miocene and probably Pliocene. No obvious field evidence of unconformity is noted within the Cretaceous-Tertiary series, and the history throughout appears to be merely that of orogenic movement. The folding at about the close of the Tertiary, which gave rise to the Cape Range, is of more than ordinary interest as being the only instance of its kind recognized in Western Australia.[4]

TERTIARY AND CRETACEOUS STRATIGRAPHY.

Outcrops of Miocene and later formations appear in numerous deeply eroded gorges in the Cape Range, and extensive outcrops of Miocene, Eocene and Upper Cretaceous strata are to be seen in the Giralia Range to the east. Southward along and near the Coast are coquina limestones, consolidated beach sands and various unconsolidated deposits, probably in large part post-Tertiary and almost devoid of structure other than that of a depositional nature. Here and there throughout the coastal plain are large areas covered by ridges of wind-blown sand.

The Cape Range.—The Cape Range is a broad structural uplift rising to elevations of around 1,200 feet in the central portion and falling off to the north and south. Judging from the topography, which approximately reflects the structure, it is not a simple rounded anticline but composed of a principal fold with various lesser undulations. In some respects it is comparable with certain slightly denuded structures in California such as Elk Hills. The average breadth is about 10 miles and the length 60 miles. On the east slope are several deeply cut canyons extending far back

[4] Post-Jurassic faulting is reported by Woolnough and Somerville in the Irwin River Area. (A Contribution to the Geology of the Irwin River Valley of Western Australia. Jour. Proc. Roy. Soc. New South Wales, vol. 58, pp. 67–112, 1924.)

into the Range, and strata of this side show dips of around six degrees, but progressively gentler upstream. Drainages on the seaward side also are deeply incised but are shorter. The slopes rise in several successive steps as elevated sea cliffs and wave-cut terraces ranging from about 20 feet above sea level up to 180 feet. The lowest forms a continuous coralline bench one-half to one mile wide, along which a rough motor road extends northward to Northwest Cape and thence down the east side. The anticlinal character of the Range is only imperfectly evident in the rocks composing the seaward side, since the later rocks are elevated reef and beach deposits which, in part, post-date the folding. The thickness of strata exposed in the deeply eroded canyons on the east side is probably around 900 feet. The upper several hundred feet consist of compact gray limestone in thin to thick beds, containing poorly preserved fossils. Beneath this are somewhat more than 500 feet of chalky to granular, friable, open-textured limestones abounding in foraminifera and containing occasional layers rich in echinoids. Fossils from these lower beds point to Lower Miocene age, according to F. Chapman, Commonwealth Paleontologist, who states that in view of the abundance of *Eulepidena murrayana* (form B), along with nephrolepidenes and an occasional *Miogypsina,* the age is apparently Aquitanian, (lowest stage of the Lower Miocene).[5]

Vicinity of Exmouth Gulf.—Around the head of Exmouth Gulf and southward are several low hill ranges including Rough Range and Giralia Range, which stand out as evidence of the mild folding in this part of the Basin. The Giralia Range, extending southward from the Gulf for 80 miles to the vicinity of Salt Lake, and along which are numerous mesas and conical hills such as Remarkable Hill, is anticlinal in the northernmost portion. The Cretaceous-Tertiary contact is exposed at intervals throughout, and little if any evidence of unconformity was noted. The Cretaceous beds are of exceptional interest because of their rich molluscan fauna, which include one new genus as well as new species

[5] The Cape Range was first described by Clapp, and his fossil collections from strata low in the section were also submitted to Chapman, who then regarded them as of Oligocene age but, on the basis of additional material, now revises his views.

in formational zones not heretofore recognized on the Continent. The Tertiary consists of friable, open-textured, chalky limestones with a thickness of a little more than 300 feet. Specimens from the lower third, collected near the Giralia-Bullara Road, yielded tests of *Discocyclina* and *Actinocyclina* which, according to Chapman, establish the age as Eocene. Higher beds are rich in bryozoan remains and echinoids, probably Lower Miocene. The uppermost beds forming the outer flanks consist of clastic limestones containing abundant shell fragments of *Inoceramus* derived from erosion of a Cretaceous horizon rich in that fossil.

The strata comprising the Cretaceous in the Giralia Range as listed in descending order include, (*a*) two feet of foraminiferal, glauconitic sand; (*b*) several feet of marly clays abounding in large and small fossils with *Eubaculites* and other cephalopods particularly in evidence; (*c*) about 75 feet of argillaceous, calcareous shales thickly interlain with platy aragonitic *Inoceramus* shells; (*d*) gypseous, gray diatomaceous shales. Collections from horizon (*a*) at Mile Post 20, near the southeast corner of Bullara Station, revealed 62 species of foraminifera as examined by Chapman. The fossil assemblage of horizon (*b*) was reported on by F. W. Whitehouse of Brisbane University, who found the ammonites of particular interest and including one new genus. The age is probably Lower Campanian, thus indicating the youngest Cretaceous fauna yet discovered in Australia.

The preliminary list of Cretaceous macrofossils by Whitehouse includes 30 species, and a list of some of the *Ammonoidea* is given here, since they are regarded as a delicate criterion of the age:

Eupachydiscus (?) sp.; *Paropochydiscus* sp. (cf. *compressus* Spath); *Schluetheria* aff. *simplex* (V. Hoepen); *Schluetheria* sp. (aff. *rousseli* Grossoeuvre); *Moorites* sp.; *Hauericeras* sp.; *Eubaculites* aff. *vagina* (Forbes); *Diplomoceras* (?) sp.; "*Hamites*" sp.; Gen. nov. (aff. *Nipponites* Yabe) sp. nov.; *Phylloceras* aff. *forbesianum* (d'Orbigny).

The following foraminifera were identified by Chapman from glauconitic sands lying immediately above the beds from which the above-listed *Ammonoidea* were collected. The locality is a creek bed at Mile Post 20, near the southeast corner of Bullara Station.

Haplophragmoides latidorsatum
Haplophragmoides, cf. *rugosum*
Dorothia sp.
Clavulina parisiensis
Clavulina angularis
Gaudryina rugosa
Marssonella oxycona
Spiroplectammina anceps
Arenobulimina sp.
Bulimina imbricata
Bulimina elegans
Buliminella obtusa
Guembelina globulosa
Rectoguembelina sp.
Lagena aspera
Lagena laevis
Lagena hexagona
Nodosaria cf. *annulata*
Nodosaria marcki
Nodosaria obscura
Nodosaria prismatica
Nodosaria lepida
Lenticulina sp.
Saracenaria italica
Gonatosphaera sp.
Pseudopolymorphina sp.
Sigmoidella elegantissima
Guttulina cf. *woodsi*
Globigerina bulloides
Globigerina cf. *dutertrei*
Globigerina triloba
Nodosaria inflata
Nodosaria vertebralis
Nodosaria velascoensis
Dentalina consobrina
Dentalina cf. *monile*
Dentalina adolphina
Dentalina cf. *obliqua*
Dentalina cf. *ewaldi*
Dentalina nana
Vaginulina trilobata
Vaginulina sp.
Vaginulina strigillata
Marginulina sp.
Flabellina sp.
Frondicularia cordai
Frondicularia cf. *sherborni*
Lenticulina muensteri
Lenticulina cf. *discrepans*
Lenticulina diademata
Lenticulina subalata
Lenticulina subalata var.
Lenticulina gaultina
Pullenia quaternaria
Discorbis sp.
Anomalina rubiginosa
Anomalina pertusa
Anomalina ammonoides
Cibicides ungerianus
Cibicides haidingerii
Cibicidella variabilis
Eponides sp.

Winning Pool and Southeastward.—Cretaceous exposures lower than the *Inoceramus* horizon outcrop at a number of points in the vicinity of Winning Pool. The rock consists of a siliceous, punky, light-weight, gray to white siltstone varying from thin-bedded to massive and structureless. Specimens examined are composed largely of radiolarian remains and lesser amounts of diatoms along with a few lamellibranch shells, and the belemnite *Dimetobelus diptychus* (McCoy). The age of the beds, based on distinctive genera of *Radiolaria,* is regarded by Chapman as Upper Albian (highest Lower Cretaceous), and he remarks that

the assemblage is identical with that at Fanny Bay, Port Darwin. Southeast of Winning Pool and southward for many miles are scattered mesas and tablelands of these beds. Chertiness is usual in the upper weathered portion. These basal Mesozoic strata as traced northeastward are seen to overlap the Permo-Carboniferous and underlying crystalline rocks.

It should be explained that the area represented as Cretaceous in the present geological mapping has heretofore been indicated on published maps as Jurassic.[6] Ample evidence is now in hand as to the Cretaceous age of the lowest as well as highest beds of this interval. Although the presence of Jurassic in neighboring areas to the northeast and south is not disputed, it seems that beds of that age are either thin or absent over much of the Northwest Basin. The nearest known occurrence is to the south near Geraldton, where a collection of fossils made many years ago was identified by Chapman as Jurassic.[7]

PERMO-CARBONIFEROUS (KAMILAROI) STRATIGRAPHY.

The only Paleozoic strata in the Northwest Basin are Upper Carboniferous and Permian, which, for convenience, are included under the name Kamilaroi—a term which was introduced in New South Wales. Devonian as well as other earlier systems are present in the Desert Basin. Kamilaroi deposition was initiated under fluviatile to shallow marine conditions adjacent to a fairly elevated region then undergoing glaciation. Arkosic sands, rock-flour silts, gravels and successive boulder beds were laid down to thicknesses of as much as 2,200 feet. Glacial origin is witnessed by presence of striated boulders and other characteristic features. That deposition took place in part beneath the sea is proved by the presence of marine fossils at several horizons. A small cup coral and productid brachiopod were found on the Lyndon River at a horizon 1,500 feet below the top of the formation. Earlier observers remark on a boulder bed, the Lyons Conglomerate,

[6] Geological map of the Commonwealth of Australia, by Sir T. W. Edgeworth David. March, 1931.

[7] Chapman, F.: On some *Foraminifera* and *Ostracoda* from Jurassic strata near Geraldton. Roy. Soc. Victoria, March, 1904.

considered to be a persistent marker traceable not only through the Northwest Basin but also in neighboring sedimentary areas including the Irwin River region to the south. More detailed studies by Raggatt lead to revised conceptions concerning the Lyons, and it becomes evident that, instead of there being a single persistent conglomerate member, such beds occur at numerous horizons distributed through a considerable vertical range. For instance, eight different boulder beds closely resembling the one described by Maitland were found on Wyndham River, a tributary of the Gascoyne. It is to be remarked, however, that boulder beds are particularly prevalent near the top of the formation over large areas in the Lyons River region, the locality from which the name is taken. In view of the discontinuous character of these beds and their great vertical range, it is now proposed to use the term "Lyons" as a formational name to designate the entire aggregation of sandstones and conglomerates.

The Lyons formation is overlain, probably disconformably, by the Callytharra limestone, the basal beds of which locally consist of an agglomeration of rounded to angular pebbles of crystalline rock and fossils including large brachiopods, all set in a limestone matrix. Higher strata vary from shaly argillaceous limestones to bedded compact limestones. Weathered outcrops of the shaly facies commonly show masses of fossils, and collections studied by Chapman have yielded more than 50 species, including a foraminiferal content closely resembling that of the Pennsylvanian of Oklahoma and Texas.

Still higher formations of the Kamilaroi sequence include two prominent sandstone formations of variable thickness and persistence, alternating with which are thick shaly formations. Marine deposition is indicated almost throughout by the prevalence of fossils, even the massive sandstones being in part fossiliferous. Black carbonaceous shales appear at various horizons, and more or less detrital carbonaceous material also is prevalent in the sandy shales and shaly sandstones. Outcrops of the Byro beds were noted in 1909 by Gibb Maitland [8] who remarks on the

[8] Geological Investigations in the Gascoyne, Ashburton and West Pilbara Goldfields. Geol. Surv. Western Australia, Bull. 33, pp. 20–21, 1909.

presence of sandy shales in the bed of the Minilya River downstream from Middalya Station, and states that: "Down the river for some distance, dark sandy micaceous shales are exposed at intervals in the form of synclinal troughs modified by faulting. These shaly beds occupy the country for about four miles below the Station."

The uppermost formation, designated the "Wandagee" from the Station of that name on the Minilya River, consists largely of shales which, being of non-resistant character, are only locally exposed in the plains area west of the Kennedy Range. Excellent exposures examined along the Minilya River in the vicinity of Wandagee Station and at points southward are seen to consist largely of fossiliferous clay shale and calcareous shale, minor amounts of carbonaceous shale, sandy shale and shaly sandstone, and small amounts of fossiliferous limestone. A feature of interest is the presence of occasional erratic boulders imbedded in the shale, which must have been transported by floating ice.

Generalized Section of Kamilaroi (Permo-Carboniferous) in descending order.

Wandagee Formation. Carbonaceous, sandy, and calcareous shale, and sandstones; erratic boulders; marine fossils; maximum thickness about 1,450 feet on Minilya River. Artesian wells show that these shales are widely distributed beneath the Coastal Plain.

Kennedy Sandstone. Massive to thin-bedded sandstones; ferruginous, fossiliferous concretions in lower part; forms the Kennedy Range from the Gascoyne to the Minilya River; thickness around 700 feet; thinner and more or less shaly farther north, and probably also southward from the Gascoyne, where outcrops are less conspicuous. This sandstone is an important artesian aquifer in the coastal plain.

Byro Formation. Gray to dark, sandy shales, black to gray shales, greenish, cross-bedded sandstones, silty, structureless mudstones, impure limestones; fossils include *Deltopecten subquinquelineatus, Chonetes pratti,* and species of *Productus.* Fossil assemblage indicates Lower-Permian age. Glacial erratic boulders seen locally in lower part. On Wooramel River, largely calcareous to shaly sandstone. Northward it becomes increasingly shaly. Average thickness around 1,900 feet from Gascoyne River northward; gradually thinning southward from Gascoyne River; maximum thickness recognized in well logs 2,330 feet.

Wooramel Sandstone. White to gray, thin-bedded to massive, micaceous

sandstone; thickness on Wooramel River about 800 feet; beds include richly fossiliferous ferruginous bands; thinning northward, and less than 300 feet from Gascoyne River northward.

Callytharra Limestone. Probably lies disconformably on Lyons; upper part consists of compact, yellowish-green, thin-bedded limestone with shale intercalations; lower part calcareous, shaly mudstones interlain with thin, hard calcareous bands and with basal conglomerate consisting of glacial gravels in calcareous matrix; thickness 80 feet on Wooramel River and up to 460 feet northward from Gascoyne River where hogback ridges of the limestone are prevalent. All parts are highly fossiliferous; Upper Carboniferous, according to F. Chapman.

Lyons Formation. Gray to white siltstones, fine to coarse-textured sandstones, finely pebbly to coarsely conglomeratic and bouldery beds; glacial striated boulders; deposits probably largely marine and containing corals, brachiopods and other fossils; thicknesses up to 2,200 feet; boulder beds occur at various horizons.

PRE-CAMBRIAN.

The Kamilaroi beds rest on a pre-Cambrian floor throughout the area. Those rocks consist largely of schists and granitic to dioritic gneisses but over considerable areas are quartzitic sandstones and shaly beds, the Mosquito Creek series, regarded as older Proterozoic.

GROUNDWATER CONDITIONS.

The groundwater level lies at a considerable depth below the surface over much of the region. Springs are occasionally met with in the more rugged country, particularly along the slopes of the Kennedy Range, but none in the Cape Range. The spring waters are fresh, and the same is commonly true of water derived by drilling into the Kennedy Sandstone short distances down dip from the outcrop. Artesian flows derived by deeper drilling far basinward are commonly too brackish to be potable but are fairly satisfactory for stock. Certain wells in the Lyons formation are so saline as to be of no use whatever, for example Byro No. 2 near Wooramel River, depth 2,218 feet, which encountered salty water from shallow depths downward. Instances such as this are suggestive that waters in more basinward areas may be approximately connate, and that there has been only partial flushing through groundwater movement.

The Mesozoic rocks are less sandy and are not good carriers of artesian water. Small flows are commonly obtained in wells drilled into the basal beds of the series and sub-artesian wells are numerous. The waters are characteristically brackish but are fair water for stock.

OIL AND GAS INDICATIONS.

No seepages of oil or gas are known anywhere in the basin. Very little direct evidence of oil or gas has been reported in the numerous holes drilled for water. It has been remarked that, if the region is petroliferous, proof should be encountered in the numerous holes drilled for water. One reported discovery is described by M. J. Hannay, an experienced driller in the Northwest, who reports that when putting down the Jam Thicket well on Mia Mia Station, near Lyndon River, " oily matter " appeared after pumping the slurry. This slurry would drain away 60 feet and, on being touched with a lighted match, would burn its full length. This hole probably commenced in the lower shaly Byro beds. A description such as this strongly suggests that inflammable gas, at least, was encountered. The same driller states that he has observed a similar occurrence with the slurry in drilling other wells. A further report concerning gas encountered in a well drilled on Mia Mia Station was submitted by a Mr. House, driller, who states that quantities of gas were present in the bore, so much so that it used to be lighted for the edification of visitors.

From Davis, Hankinson & Co., of Perth, who have been in the business of water-well drilling for many years, comes the statement: " In the Northwest, it is quite a common occurrence to strike sufficient gas when drilling in the Black Shales to light at the bore head."

Of the 80 or more water wells drilled to depths exceeding 500 feet in the area extending from Onslow south to the Wooramel River, about 44 started in or were drilled into the Permo-Carboniferous. It will be noted from the maps that most of these are grouped along the Lyndon and Minilya River valleys and

thence southward near the Coast. No deep wells have been drilled within 25 miles of the Exmouth Gulf-Cape Range area. Homoclinal to synclinal structural conditions probably prevail over most of the area to the south where deep drilling has been done. The absence of reliable evidence as to oil shows would be more significant were it known that some of the deep wells were located where the structure is favorable.

In wells drilled for water, the objective is commonly achieved by penetrating basal Mesozoic porous beds or, on failure there, the highest persistent sandstones of the Permo-Carboniferous; therefore, few have been drilled far into the Permo-Carboniferous. Good results are usual from the Kennedy sandstone, which in some localities lies immediately beneath the Mesozoic overlap, and in others as much as 1,450 feet deeper, depending on the amount of Wandagee shales present.

Judging from evidence in certain oil regions of America where geological conditions are comparable with those here, it is surmised that, even granting oil is present, it will be encountered in the artesian water beds only under exceptional conditions. This view is based in part on the observation that the thick water-carrying beds commonly lack intimate association with oil source-beds, and therefore, do not receive much oil, and in part on the belief that the oil may be flushed away by artesian circulation. Less persistent lenticular porous beds should be the principal oil reservoirs, especially where associated with shales of rich organic content. Considerations of this nature are discussed by Russell in a paper on the fields of Kentucky,[9] where conditions are in some respects similar to this region.

Petroleum Source Beds.

Black shales, carbonaceous sandy shales, calcareous, fossiliferous shales, shaly limestones, foraminiferal limestones, and diatomaceous, radiolarian shales—all deposited almost entirely under marine conditions—comprise substantial proportions of the strati-

[9] Russell, W. L.: Geology of Oil and Gas Fields of Western Kentucky. Bull. Amer. Assoc. Petr. Geol., vol. 16, no. 3, pp. 231–254, 1932.

graphic column. Richly organic rocks such as these are regarded as probable petroleum source-beds. Certainly, comparison of the stratigraphic and lithologic composition here with that of petroliferous regions elsewhere, for example the Appalachian fields of America, reveals no obvious reasons why one should not as well be petroliferous as the other.

A recently published paper on petroleum and gas in Pennsylvania by Torrey is of interest in this connection.[10] He states that chemical and geological evidence indicates a probable vegetable origin for much of the petroleum and natural gas produced, the oil coming from source beds which have a rich microflora and the gas being derived in part from coarse vegetable residue. The fields are restricted to areas where marine reservoir rocks are present and where source rocks are in contact or closely associated with the productive sandstones.

Apprehension as to the probable adverse influence of a cold climate on the distribution of oil fields is expressed by Arthur Wade, in a paper presented at the World Petroleum Congress, London, 1933.[11] His views as summarized by V. C. Illing, General Reporter,[12] are as follows: The occurrences of glacial boulder beds at various horizons in the west, and tillite as well as erratic boulder occurrences in the east of Australia are cited as evidence of probable cold climatic conditions during much of Permo-Carboniferous time. After a discussion of the Paleozoic history of the United States in terms of the relation of this land mass to the belts of equatorial climate, he concludes that the evidence supports the view that the richness of the Paleozoic rocks of the United States in petroleum was the result of the climatic belt in which these rocks were deposited, the warm conditions favoring organic life, and from similar reasoning he concludes that Australia has little hope of oil production in its Paleozoic rocks.

[10] Torrey, Paul D.: Origin, Migration and Accumulation of Petroleum and Natural Gas in Pennsylvania. A part of the symposium on Problems of Petroleum Geology, Amer. Assoc. Petr. Geol., 1934.

[11] Wade, Arthur: The Distribution of Oilfields from the View-Point of the Theory of Continental Spreading. World Petroleum Congress, London, 1933, vol. 1, pp. 73–77.

[12] *Idem*, p. 2.

If richly organic deposits such as black shales, coal beds, and fossiliferous, shaly limestones were but poorly developed in the Permo-Carboniferous of Australia, there might be some basis for the doubts expressed by Wade. Such is not strictly true, however, either in the east or the west, and certainly the opposite is true as regards the Northwest Basin, whatever the climate may have been during the time of deposition.

In this same connection it should be remarked that F. Chapman finds substantial paleontological evidence in support of the view that the sea waters of Australia were comparatively warm during "Lower" and "Upper Marine" times. His views are as follows:[13]

> The Callytharra fauna chiefly comprises crinoidal limestones, rich polyzoal beds and occasional solitary and dendroid corals. On the face of this evidence we may assume that the climatic belt of this area in Upper Carboniferous times was decidedly warm.
>
> The same may be said for the climate of the Lower Marine (Lower Permian) beds of the Fossil Cliff outcrops, Irwin River. There we find a foraminiferal phase showing many species in common with both the Pennsylvanian and Permian of Texas (Upper Carboniferous to Middle Permian). A marked difference in the Australian foraminiferal fauna of this period, however, is the entire absence, up to the present, of any of the fusulinids (*Verbeekina, Fusulinella* and *Neoschwagerina*) such as are found in Sumatra and Timor (Tobler, 1910).
>
> We may therefore assume that the warm temperate climatic belt of the Lower Permian of Western Australia was just outside the East Indian tropical zone certainly denoted by those fusulinids.
>
> The successive glaciations found in the Kamilaroi Series of Australia could have had no very drastic influence in cooling the shallow marine areas, as we may see by the abundant life of the Lower and Upper Marine Series. Its Spirifers and productids, especially in Western Australia, closely match the species found in the *Productus* limestone of the Salt Range in India.

The studies of Trask go far towards uprooting certain fixed ideas among geologists regarding deposition of petroleum source-materials.[14] For instance, he refutes the popular idea as to the

[13] Communicated in letter dated March 6, 1935.

[14] Trask, Parker, D.: Origin and Environment of Source Sediments of Petroleum. Amer. Petroleum Institute, 1932.

importance of estuarine deposits through finding that sediments accumulating under estuarine and deltaic conditions are commonly poor in organic content. And equally interesting to those who think of tropical seas as a most favorable environment are his findings as to the seeming unimportance of climate. Richly organic sediments are now accumulating in cold waters as well as warm. He finds that the organic content of bottom muds from certain localities in far northern or southern latitudes, including parts of Bering Sea, Aleutian Islands, Baltic Sea and Kerguelin Islands (latitude 50° south), is only moderately less than the content of sediments deposited under similarly favorable environmental conditions in much warmer climatic zones. And under the heading, "General Remarks on Tropical Environments," p. 143, he states: "The organic content of tropical nearshore sediments is similar to that of temperate and arctic deposits."

Reservoir Rocks and Cover.

The adverse conclusions of Clapp as to oil possibilities in the area under consideration were presumably based largely on the supposed dearth of impervious shales, since he states[15] that: "Only a few feet of shale were actually seen or authentically reported in the Basin." That stand is without basis in view of the fact that various parts of the Kamilaroi, and particularly the upper two thirds, as now known, comprise substantial amounts of shaly beds at successive horizons. As to lithology, all gradations from mudstones and clay shales to calcareous shales and sandy shales are included. Some of the strata of richly organic composition suggestive of source beds also appear to offer promise of being good cover rock. These remarks as to the prevalence of impervious strata, though true as regards the Kamilaroi Series, are not closely applicable to the Mesozoic and Tertiary. Those strata consist largely of lithologic types of a more pervious character, such applying particularly as regards the Tertiary and the uppermost Cretaceous. It is surmised, however, that the argillaceous facies immediately beneath the *Inoceramus* horizon in the Cretaceous may serve as a seal to upward migration

[15] Oil Prospects of the Northwest Basin of Western Australia. *Op. cit.*, p. 1148.

Question frequently arises as to the identification of lithologic types as logged by drillers. For instance, the drillers apply terms such as "shale," "black-Jack" and "flint." Clapp concluded that the term "shale" is commonly applied to any fine-grained rock in Western Australia. Although logs in the coastal plain, adjacent to areas of outcrop, designate certain fine-grained rocks with partings as "shale" whether argillaceous or not, and some of the aquifers also as "shale," Raggatt finds that the uppermost beds in the Kamilaroi succession, and the shales of the Cretaceous have to a large extent been correctly logged, the latter with descriptive terms such as "sticky," "green," etc. commonly prefixed.

Character of the Coals.

No coal beds have been observed in this area and it is doubtful whether any exist, although in some localities there are black, highly carbonaceous beds in the basal portion of the Byro which approach an earthy coal in composition. The nearest coal occurrences are in the Irwin River Valley, 220 miles south of Wooramel River, where the "Coal Measures" contain several beds of the bituminous type which have been prospected at various points by shaft sinking and core drilling.

Although the Kamilaroi beds as exposed on Irwin River appear to be in less substantial development than in the Northwest Basin Area, various parts of the columns of the two areas show resemblances that permit approximate correlation. It is surmised that the Irwin River "Coal Measures" are approximately related to the basal Byro beds of the north.

The few analyses of the Irwin River coals show carbon ratios ranging from 54 to 63. The percentage of moisture is high in most samples, ranging from around 10 per cent. as an average to more than 20 per cent. in certain impure high-ash coals.[16] Thus the evidence as to degree of alteration furnished by the coals is favorable. And since the general geological setting in the Irwin River area resembles that of Northwest Basin, it is reasonable to assume that the same evidence also is applicable there.

[16] Annual Progress Rept., Geol. Surv. Western Australia, 1922, pp. 11–13.

SUMMARY.

The purpose of the foregoing paper is to present recently obtained geological particulars and deductions as to oil possibilities of the Northwest Basin. Previously published reports based on hasty reconnaissance present an array of unfavorable assertions such as (*a*) supposed scarcity or absence of source beds; (*b*) almost entire absence of shaly beds; (*c*) predominance of persistent sandstone formations, ideal carriers of artesian water but unfavorable for retention of oil; and (*d*) absence of oil and gas indications in the many wells put down for water. Certain unfavorable features still hold, but the substance of the new data is such as to place the region in a relatively attractive rating. The total measured thickness of Upper Carboniferous and Permian strata exceeds by several thousand feet the amount heretofore known; the series includes substantial thicknesses of richly organic shales and other potential source beds, as well as shaly beds which should serve as seals; and within the shales are lenticular reservoir beds. Additional favorable features are the mild structural deformation characteristic of this in common with all of Western Australia, and the moderate degree of carbonization of the coals. No tests have ever been put down in the search for oil; showings of inflammable gas are reported in several instances during the drilling of wells for water. Failure to encounter shows of oil in wells drilled into the Permo-Carboniferous is not conclusively significant, since drilling in most instances stopped in the uppermost artesian water horizon, a persistent sandstone formation high in the stratigraphic column. Large portions of the possibly petroliferous series remain practically untested. Furthermore, most of the wells have been drilled in areas probably either synclinal or homoclinal, and certain other areas known to be underlain by favorable structure have never been touched by the drill.

SYDNEY, AUSTRALIA,
April 8, 1935.

GEOLOGIC PROBLEMS OF THE CANADIAN PRE-CAMBRIAN GOLD-FIELDS.

E. Y. DOUGHERTY.

INTRODUCTION.

Discussion of research problems of ore deposition at the joint meeting of the American Institute of Mining Engineers and the Society of Economic Geologists in February, 1935, brought out the desirability of fuller exposition. Everyone concerned with the study and application of economic geology doubtless feels the need of more facts, more established principles, more correlation and co-ordination, more synthesis. There is hardly any branch of the science or art that does not need research.

Some geologic problems pertaining to the Canadian pre-Cambrian Shield gold-fields are suggested and discussed in this article, followed by brief comment on means and methods of study. The suggested problems are believed to be of universal interest and importance to the science of ore deposits and to the practice of mining geology; and of particular importance to prospecting, exploration and development of Canadian Shield gold areas and deposits, as well as similar areas and deposits in other countries.

All these problems are parts of the problem of distribution and localization of gold ore, and many others than those listed might be suggested. Those dealt with include most of the problems found or judged by the writer to be especially pertinent to the search for gold ore in the Canadian Shield. The aim of the studies is to correlate, co-ordinate and explain relevant geologic data bearing on this fundamental problem. A part of the uncertainty regarding gold localization, expressed in the popular phrase that "gold is where you find it," arises from incomplete accumulation of facts and inadequate correlation of known facts. In spite of the variability and complexity of the factors affecting

gold localization, it seems evident that principles universally applicable, although imperfectly understood, do exist. It is believed that much fuller understanding can be obtained on many questions by *comparative* studies of many areas. Hence, an inherent feature of all the studies suggested is comparison of facts from area to area and from mine to mine, and the correlation and co-ordination of these facts to attempt to discern and explain similarities and differences. Unusual opportunities and great economic incentive to pursue such studies exist in the Canadian Shield goldfields.

SUGGESTED PROBLEMS.

1. The positions of major and minor gold-producing zones with respect to the margins, configuration and disposition of granitoid batholiths.
2. Structural relations and space positions of granitoid batholiths with respect to the regional structure, major deformations, and major dislocations of gold-containing rocks.
3. The relation between ages and types of granitoid batholiths and gold distribution.
4. The distribution, space positions, configuration and disposition of porphyry intrusives with respect to gold zones and the structure of the intruded rocks.
5. The relation of intrusives to associated gold deposits.
6. The localization of gold areas and mines with respect to regional structure.
7. The localization of gold mines and ore shoots with respect to particular rock structures.
8. The structure of gold-quartz veins and lodes, with special emphasis upon the economic importance of the structures.
9. The relation between gold occurrence and the physical, chemical and mineralogical nature of wall rocks.
10. The relation between gold occurrence and the kind, quantity, and distribution of wall-rock alteration.
11. The relation between gold occurrence and the kind, quantity and distribution of metallic and non-metallic lode and vein minerals.

12. The distribution of gold-associated metallic minerals with respect to geologic conditions.

COMMENT ON SUGGESTED PROBLEMS.

1. Positions of Gold Zones with Respect to Granitoid Batholiths.—It is now generally believed that the Canadian Shield gold deposits originated from solutions that were differentiated from granitoid magmas. Work such as is being pursued by W. H. Emmons is presenting illustrations, some of which are from Canadian Shield areas, of the position of ore deposits with respect to the margins, configuration and disposition of granitoid batholiths. The findings are of great importance to prospecting and to understanding of the conditions favorable for gold distribution and localization. The Canadian Shield gold-fields afford evidence of the usual absence or paucity of important gold-quartz deposits well within the granitoid bodies. Certain other conclusions are indicated, but the entire question needs fuller study.

2. Structural and Space Relations.—It is recognized that the important gold deposits lie in or near belts of more or less deformed and dislocated rocks that are bordered or surrounded at variable distances by granitoid batholiths and presumably underlain at various depths by these batholiths. It would appear to be of great interest and possible economic utility to augment present published vertical geologic sections by a large number of additional cross-sectional and three-dimensional views showing the gold zones, batholiths, regional structures, and rock deformation and dislocations across the Canadian Shield. With such a foundation, illuminating judgments of economic value may result.

3. Age and Types of Batholiths and Gold Distribution.—The older granitoid batholiths of the Canadian Shield, commonly called Laurentian, are believed generally to be unassociated genetically with important gold deposits, whereas the later Algoman batholiths are thought to be the major associates. Still later batholiths, termed Killarney, are judged to be sources of gold in places, notably north of Lake Huron. Although many maps show the

distribution of the batholiths, there is need for a closer scrutiny of the evidence and its further correlation and co-ordination with gold occurrence. It would seem to be worthwhile to explore fully the evidence as to what extent physical, chemical and mineralogical variations in granitoid batholiths have a significant relationship with gold distribution. In this problem variations in the structure, texture, differentiation, contact relations, alteration, chemical composition, mineralogical constitution, and other features could be correlated with the variable productivity of the numerous zones intruded by batholiths in the Canadian Shield.

4. Porphyry, Gold Zones and Structure.—Although this problem is commonly of vital practical importance to the gold mines of the Canadian Shield, the facts and their significance have yet to be dealt with comprehensively. Much evidence is available in maps and reports on many gold mining districts, and much more evidence could be obtained. Broadly, it is generally believed that porphyritic intrusives, like the associated gold deposits, have been emplaced frequently in or near zones of deformation and (or) dislocation, and that the disposition of both the porphyry intrusives and gold zones have been much influenced by the structure of the country rocks. Great economic importance attaches to a comparative detailed study of the special conditions most favorable for commercial concentration of gold.

5. Relation of Intrusives to Associated Deposits.—This may include comparative studies of the kinds of intrusives and the kinds of associated gold deposits; time, space, and structural relations of the intrusives to the associated gold deposits; genetic relations of the intrusives and associated gold deposits.

It appears to be generally a fact that the more important gold-quartz deposits of the Canadian Shield lie in, next to, or in the general vicinity of intrusives in which quartz and (or), albite (less commonly potash feldspar) are conspicuous or predominant minerals. Commonly these quartz- and albite-bearing intrusives have a porphyritic texture. That there is genetic association of intrusives, particularly porphyries, and gold is firmly believed by the majority of persons connected with mining in the Canadian Shield. Much prospecting and exploration is directed with space

relation as a practical guide and with genetic relation as an underlying principle. Yet it must be admitted that ideas and explanations are frequently foggy, if not faulty or erroneous. There is much need for a thorough assembling of the facts, their correlation, and their critical study and analysis. Other kinds of intrusives than the salicic or alkaline porphyries are involved in the problem, including diorite, gabbro, diabase and lamprophyre, which are commonly associated in space, and in some cases apparently closely associated in time, with the gold deposits. Sulphide deposits of copper and gold, such as Noranda, may have especially involved relations with associated intrusives. Given satisfactory data on the physical and chemical nature of the intrusives and the gold deposits, and on space, structural and time relations, one may then invoke hypotheses and principles of magmatic differentiation and of physical chemistry to help in explaining genetic relations. The field is broad and challenging and of great economic importance.

6. Gold Areas and Regional Structure.—The localizations of gold areas and mines are generally in synclinal belts, or near the borders of them, particularly where sedimentary rocks, commonly called Temiskaming, occupy the belts. Limbs of regional synclines appear to be particularly favorable. Although this general relation has been pointed out, a thorough assembling of the data, including analysis of deformation, dislocation, positions with respect to synclinal axes, cross-folding, pitch and attitude of folds, and other conditions, awaits comprehensive study.

7. Localization of Gold in Particular Rock Structures.—There is abundant information bearing on this problem available at the mines and in the surrounding country. At the February meeting of the American Institute of Mining Engineers, J. E. Gill showed some illuminating pictures of structural conditions at Quebec gold mines. A volume could be written on the subject. Perhaps there is no single geologic problem of more practical interest to prospectors, mining geologists and mining men of the Canadian Shield gold areas.

Although many strongly deformed or dislocated zones are not ore-bearing, many of the important gold concentrations un-

doubtedly occur in or near these zones. To picture and interpret these conditions so that general principles will appear in clearer relief is a task well worth the large amount of detailed work it entails.

8. Structure of Gold Lodes.—Practically every imaginable structure of gold-quartz veins and lodes can be found in the Canadian Shield. Certain structures are known or believed to be characteristic of the more persistent ore bodies; others, to be more erratic and discontinuous. The influence of the physical nature of the country rock upon vein and lode structures is of much practical importance. How variable structures of the veins and lodes affect localization, continuity, attitude, size, mine-ability, depth persistence, and tenor of ore in Canadian Shield gold-quartz deposits are questions of economic importance. Much of the evidence is to be found in the operating mines.

9. Relation of Gold to Wall Rocks.—Physical influence of wall rock is commonly recognized; chemical and mineralogical influence is generally enigmatic or imperfectly perceived. Important physical factors are the relative brittleness or toughness of the wall rocks, their relative massiveness or schistosity, and their relative "competency." An outstanding example of the apparent influence of chemical and mineralogical nature of wall rocks is the usual low gold-content in veins and lodes contained in quartz porphyry at Porcupine as compared with the gold content in veins or lodes contained in adjacent lavas or sedimentary rocks. Much evidence exists on the problem. Its comprehensive study is feasible and important economically.

10. Relation of Gold to Wall Rock Alteration.—This involves correlation of gold occurrence with such well-known processes as carbonatization, albitization, sericitization and chloritization of wall rock. It appears to be clearly indicated that the relative intensity and character of these alterations is reflected in variable gold-content in many mines and districts. Comparative studies of many examples would bring to light more clearly the extent to which various alterations can be relied upon to determine judgment on the probable productivity of various quartz veins, lodes

and zones. Comparison of gold-content where wall-rock alterations have been weak or practically absent with gold-content where such alterations have been relatively strong, as well as correlation of gold-content with kinds of alterations, should be made between districts, mines, and mineral bodies within the same mine.

11. *Relation of Gold to Gangue and Ore Minerals.*—Variations of gold tenor with variations in the vein and wall-rock mineralization are well indicated in various mines, although thorough studies of these variations are rare. Comparison of such variations in one mine or district with variations in other mines and districts are especially needed in order properly to explore the problem. Significant metallic minerals like pyrrhotite, arsenopyrite, molybdenite, magnetite, hematite, and chalcopyrite, and such non-metallic minerals as albite, potash feldspar, tourmaline, green mica, sericite, biotite, scheelite, calcite and ankerite, are especially diagnostic.

Types of pyrite deserve special emphasis. In some mines, such as those of Porcupine and Kirkland Lake, fine-grained disseminated pyrite in intercalated and included wall rock is favorable for gold concentrations; in others, such as the Howey mine in northwest Ontario and the Bussieres mine in Quebec, coarse pyrite in quartz is favorable. The disseminated pyrite of some quartz veins may carry little or much gold. Heavy pyrite aggregations may or may not be auriferous. Variations of the pyrite in grain or crystal habit, in relative age, in degree of fracturing, in associated vein minerals or associated wall-rock alterations may affect gold tenor.

Correlation of gold-content with kind, quantity and distribution of various carbonates is an important part of the problem. Certain types of the abundant carbonate of the Canadian Shield goldfields are associated with important gold deposits, other types are unassociated.

Types of quartz merit special study. Many mining men and prospectors of the Canadian Shield gold districts stress the bearing of the type of quartz on gold occurrence, but so far no one has studied the question comprehensively and scientifically. It

is frequently pointed out in reports on many districts that well-fractured quartz is favorable for gold. Other references to types of quartz favorable for gold are found in reports. Quartz bodies characterized as " sugary " or " glassy " (bull quartz) are commonly regarded as unfavorable, whereas " milky " quartz is commonly considered favorable. Well fractured or relatively unfractured quartz; gray, blue or otherwise colored quartz; clear quartz; impure quartz; fluid-containing quartz; variably grained quartz; are among the types frequently considered indicative of favorable or unfavorable conditions for important gold depositions. Comparative studies of the facts for a large number of veins are needed to test and amplify present opinions based mainly on practical experience.

One of the outstanding contributions that significant mineralogical correlations with gold occurrence can provide, is to assist judgment of the economic importance of quartz veins and lodes from inspections of their outcrops. Although a number of important guides are now of value, the evidence and its interpretation need searching inquiry.

12. *Distribution of Associated Metallic Minerals with Respect to Geologic Conditions.*—This broad problem is one upon which much suggestive but uncorrelated evidence exists. Geologic conditions may include metallogenetic provinces related to magmatic differentiation; zonal relations to various types of granitoid batholiths; relative temperature, depth, and pressure existing when and where the minerals were formed; associated intrusives; variations in wall rocks; variations in structural conditions; age and other factors. Certain gold-quartz zones, such as that of the Granada-McWatters-O'Brien belt of Quebec, are characterized by conspicuous arsenopyrite, whereas in some other belts this mineral is scarce or absent. In certain zones or areas, such as those of Noranda, Flin Flon, and the Chibougamau-Opemiska area of northern Quebec, gold-chalcopyrite ore is characteristic. Although pyrite is nearly ubiquitous, important differences in quantity and types exist. In some areas and in some mines of the same mining district, gold-associated pyrrhotite is abundant; in

others it is scarce or practically absent. A prominent example is the abundance of pyrrhotite in the Dome mine compared to its relative paucity in mines of the Pearl Lake area a few miles distant. Some minerals, such as galena and sphalerite, are indicative of high gold-content in some gold quartz bodies; in others they are absent or inconspicuous. Prospectors have a large amount of information on metallic associates of gold which they use to good advantage. The problem is admittedly difficult, but searching study and correlation of the facts would provide a basis for judgment on many economically and scientifically important questions.

MEANS AND METHODS.

Means for study of the problems include all the accumulated literature on general and metalliferous geology and related sciences; facilities and exhibits of university and government laboratories and museums; the knowledge and experience of geologists and others who have made the Canadian Shield their special field, including many in university and government circles; numerous surface exposures of gold-containing mineral bodies; many mines with easily accessible workings. For most of the Canadian Shield gold areas published geological maps and reports exist or are being prepared. Much, although of course only a part, of the essential geological data for the suggested studies is contained in these reports and maps. Many reports deal in part, directly or indirectly, with the problems in particular districts. Means for field studies are favorable. The airplane has solved quick transportation problems; practically all important gold areas are readily accessible by this and other means. Mines are usually cool and comfortable; living facilities are pleasant. One may safely affirm that not many individuals and not many mining companies would fail to co-operate in studies of problems having ore-finding as an ultimate objective. There is in Canadian mining circles a growing appreciation of the value of geological findings and geological insight, even though frequent disappointments are encountered in the use of geological theories.

Although methods of study will vary with different problems, it seems appropriate to mention some general points. Assembling of pertinent data contained in published maps and reports would appear to be a logical first step. Communication and personal contact with geologists, mining engineers and prospectors who have intimate acquaintance with the various mining areas and mines will be found helpful and valuable. For all the suggested problems, field observations are recommended as essential or paramount. The method of study should be from particular facts to generalization, in a word, by induction. Differences and similarities set side by side will reveal many important conclusions.

Who should attempt such studies as have been suggested? The question is more easily asked than answered. Particularly in such problems as the investigation of the relation of gold tenor to various factors, there would appear to be much scope for study in the geological departments of universities, because a large part of the investigation could be carried on at universities, following or along with the necessary field contacts. One might fairly consider that in all of the problems, but especially those involving much map and field work, government geologists should take the lead, with the collaboration of mine geologists and field geologists employed by mining organizations, and with collegiate geologists as collaborators also. Doubtless this would be the ideal arrangement. But government geologists have heavy demands on their time for surface geological mapping and for special areal investigations rather than for special problem investigations. The writer leaves the question open with the suggestion that interested committees, geological departments of universities, and government geological departments could do much by co-operation with privately employed geologists and with mining companies.

A final paragraph on co-operation. One of the speakers at the meeting referred to at the beginning of this article, expressed the opinion that economic geologists will not co-operate; they are too individualistic. It seems to me that statement is a challenge. A partial answer is contained in such co-operative work as the

Lindgren Volume on Ore Deposits of the Western States. In the Canadian gold-fields co-operation among mine and field geologists is certainly the rule rather than the exception. Information is usually freely given, underground and surface examinations are afforded, discussions are open, maps are accessible. When such co-operation breaks down, the reason is usually the restrictions imposed by employers. It is true, nevertheless, that there are many directions in which co-operation can be improved, for instance, in more suggestions of, and co-operative participation in, problems meriting research; the establishment of better facilities for interchange of data and information; more co-working of the privately employed mining geologist with geologists in collegiate circles; more symposiums, and more co-operative publications.

E. Y. Dougherty.

Toronto, Ontario,
May 1, 1935.

MYLONITIC SPHALERITE FROM FRIEDENSVILLE, PENNSYLVANIA.

ROBERT D. BUTLER.

INTRODUCTION.

THE peculiar appearance of some of the sphalerite from Friedensville, Pennsylvania, has long been familiar to mineralogists. Superficially, it resembles dark gray-green chert, being compact, homogeneous, and massive, with conchoidal fracture and without visible granular structure or cleavage.

This and other types of sphalerite occur in sulphide ore bodies associated with pyrite.[1] The ore bodies are found in dolomitic limestones and have been described as metasomatic replacements accompanied by minor amounts of deposition in open space. The massive fine-grained variety of sphalerite is said to have inherited its texture from the limestone host-rock.[2]

The writer studied polished sections of the ores, etching[3] the sphalerite to reveal the textures. The textures shown are incompatible with the suggested origin, and indicate instead that plastic deformation and granulation subsequent to the emplacement of the ore produced the fine-grained or mylonitic facies. Another unusual facies is thought to have been formed by recrystallization accompanying or following the deformation.

SPHALERITE FROM CHERRYFIELD, MAINE.

A specimen from a quartz-sphalerite vein, Cherryfield, Maine, shows how coarse sphalerite may be pulverized to a mylonite

[1] Miller, B. L.: Lead and Zinc Ores of Pennsylvania. Pennsylvania Geological Survey, Fourth Series, Bull. M–5, p. 60, 1924.

[2] *Idem*, p. 71.

[3] Van der Veen, R. W.: Mineragraphy and Ore Deposition (The Hague, 1925) noted the use of hydriodic acid as an etch reagent for sphalerite (p. 127) and advised the concentrated acid, specific gravity 1.96 (p. 58). Concentrated hydriodic acid, specific gravity 1.70, etching period 1–2 minutes, gives excellent results. Lesser concentrations are unsatisfactory.

within a zone of deformation and how new grain growth occurs in secondarily twinned sphalerite. Some of these relations are apparent at Friedensville, and the interpretation of the fine-grained sphalerite there is clarified by a study of the Maine specimen. The occurrence of sphalerite at Cherryfield has been briefly described.[4]

Megascopically, this specimen is mainly quartz and dark sphalerite cut by veinlets of carbonate. Small masses of galena and numerous tiny grains of pyrite are also present. Distinctly visible against this background, a band of fine-grained sphalerite, 0.5 inch wide, transects quartz and coarser sphalerite (Fig. 1). It is essentially parallel to the carbonate veinlets.

Microscopically, three well-defined textural types of sphalerite are visible: relatively coarse, with variable grain size and grain diameters mostly ranging from 0.5 to 3.0 mm.; very fine, localized in the aforementioned band, having rather uniform texture with grain diameters ranging from 0.005 to 0.01 mm.; and a transitional type with most of the grains having diameters between 0.01 and 0.1 mm.; this is localized parallel to the fine-grained band, and also occurs marginal to some of the larger grains.

Coarse-grained Type.—The coarsest sphalerite, representing original vein textures, is associated with pyrite in normal replacement relations, corroded remnants of euhedral pyrite being numerous. Alternating blebs of chalcopyrite and pyrrhotite are observed along crystallographic directions within sphalerite, and where the blebs are elongate and point towards a common intersection they contract in width, presumably indicating impoverishment of material. Furthermore, there is no evidence of replacement of sphalerite by the chalcopyrite or pyrrhotite. The writer regards chalcopyrite and pyrrhotite as having been exsolved from the sphalerite.[5] Etching reveals in the sphalerite

[4] Emmons, W. H.: Some Ore Deposits in Maine and the Milan Mine, New Hampshire. U. S. Geol. Surv. Bull. 432, p. 43, 1910.

[5] Bastin, E. S., et al.: Criteria of Age Relations of Minerals. Econ. Geol., vol. 26, p. 570, 1931.

Buerger, N. W.: The Unmixing of Chalcopyrite from Sphalerite. Amer. Miner., vol. 19, p. 525, 1934.

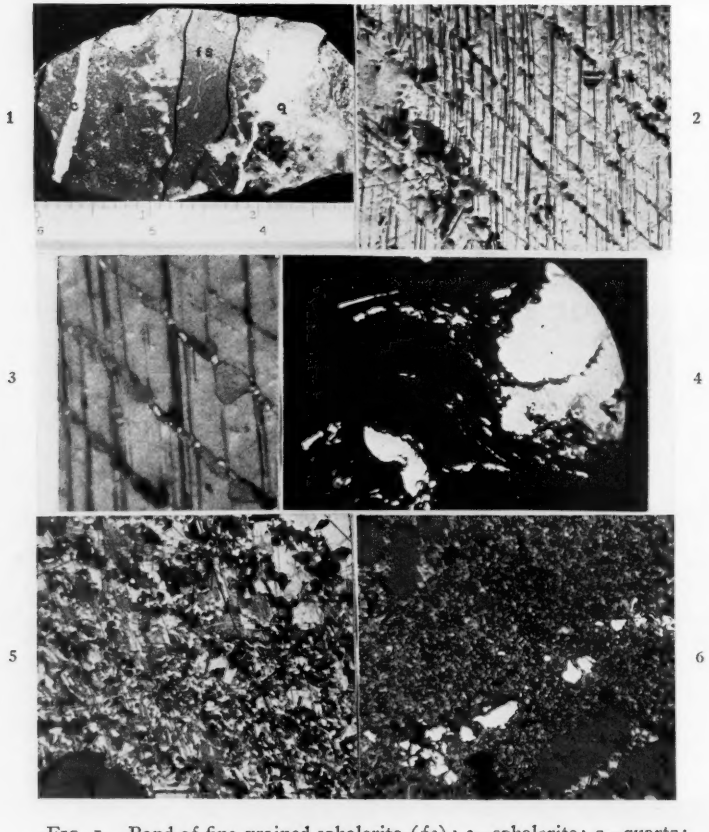

FIG. 1. Band of fine-grained sphalerite (*fs*); *s*—sphalerite; *q*—quartz; *c*—carbonate. Cherryfield, Maine.

FIG. 2. Center of large sphalerite crystal, showing traces of polysynthetic twin lamellæ in vertical direction; exsolution and recrystallization favor the inclined direction. Cherryfield, Maine. Etched, reflected light. × 60.

FIG. 3. Enlargement of central part of Fig. 2. The lighter blebs along the inclined direction are exsolved chalcopyrite and pyrrhotite, the darker blebs recrystallized sphalerite. Twin lamellae in vertical direction brought out by etching. Cherryfield, Maine. Reflected light. × 160.

polysynthetic twin lamellæ whose directions commonly coincide with loci of exsolution. Distortion of the lamellæ has been prevalent and in places they have been fractured. Smaller crystals of sphalerite are seen marginal to the larger grains and also within them. Figures 2 and 3 show exsolution preferring one direction, and secondary twinning, the other.

Transitional Type.—The transitional textural type, typically developed adjacent to the fine-grained band in a zone about one millimeter wide, is also present in small amount around some of the larger grain margins. Figure 5 shows the twinned character of some of the grains and the abrupt textural variation towards finer material on one hand and a moderate gradation to coarser sphalerite on the other. Within a microscopic field, there may be such a development of twin lamellae as to simulate schistosity parallel to the fine-grained band, but in an adjoining field the grains may not be twinned, or if twinned, may not show the microscopic parallelism. The notable features of the transitional type are the occurrences of pyrite, chalcopyrite, and pyrrhotite. Pyrite is present in rows of tiny broken fragments aligned parallel to the band, in contrast to its occurrence with the coarser sphalerite as corroded euhedral remnants. Blebs of chalcopyrite and pyrrhotite of the same size as those unmixed within the coarser sphalerite are observed interstitial to the sphalerite grains of the transitional type. There is no evidence either of replacement of sphalerite by chalcopyrite or pyrrhotite, or of replacement of these latter by sphalerite. Their interstitial habit is shown in Fig. 5.

FIG. 4. The curvature of the drawn-out rows of smaller quartz fragments in the mylonitic zone shows the buttressing effect of the large undulatory-strained quartz masses. Cherryfield, Maine. White—quartz; black—mylonitic sphalerite. Transmitted light. ×8.

FIG. 5. Gradation of coarse sphalerite into finer textures in transitional zone. Light-colored blebs are exsolved chalcopyrite and pyrrhotite after liberation to an interstitial occurrence by granulation of sphalerite; *q*—quartz. Cherryfield, Maine. Etched, reflected light. ×60.

FIG. 6. Homogeneous fine-grained sphalerite of the mylonitized zone, enclosing a row of broken pyrite fragments. White—pyrite; *q*—quartz. Cherryfield, Maine. Etched, reflected light. ×60.

Mylonitic Type.—The fine-grained band is characterized by very small equi-dimensional grains of sphalerite that are mostly twinned. Pyrite has the same fragmental character as it has in the transitional type. Fig. 6 shows the fine-grained homogeneous texture of the band and a series of pyrite fragments aligned parallel to the walls of the band. Quartz shows undulatory strain effects, fracturing, and brecciation around grain margins as well as alignment of fragments similar to the pyrite. The quartz fragments appear to have been drawn out into lenticular masses, forming trend-lines parallel to the rows of pyrite fragments and the band itself. Close examination of Fig. 1 shows series of these dark quartz lenses within the band of fine-grained sphalerite. Fig. 4 shows several of them curving around a large mass of fractured quartz.

Origin of Textures.—Recrystallization did not play a part in the development of the transitional and mylonitic textures, although it occurred in the interior of some of the large sphalerite crystals, as shown by Figs. 2 and 3. New grains have formed along crystallographic directions of the twinned sphalerite grain. Exsolution and recrystallization favored the same plane in the crystal. This manner of grain growth is similar to that shown for the Rammelsberg, Germany, chalcopyrite, where large, elongated, highly-twinned chalcopyrite crystals are surrounded by numerous smaller untwinned crystals that have grown at the expense of the larger strained ones.[6] The derivation of the smaller grains by recrystallization from the larger has been suggested at Rammelsberg because of the known deformation of the deposit, the later age of the small grains, their different habit, and their close relation to margins of the larger chalcopyrite crystals.[7]

Another criterion of this type of recrystallization, only applicable to soft minerals, however, is the presence of untwinned marginal grains which are larger in width than any of the twin lamellæ of the parent crystal. In any case, if there was a direction of slight release when the initial stress was applied to a mineral,

[6] Newhouse, W. H., and Flaherty, G. F.: Texture and Origin of Some Banded or Schistose Sulphide Ores. ECON. GEOL., vol. 25, pp. 615–618, 1930.

[7] *Idem*, p. 616.

small fragments might spall from the grain margins before minute twinning occurred. If the mineral was of moderate or greater hardness and the spalled fragments were in such a position as to receive protection from the larger grains, the larger grains could absorb any additional stress by twinning and gliding. The marginal grains might not be twinned, and the resultant texture would be similar to that of Rammelsberg chalcopyrite. If the mineral were soft or somewhat plastic, later stresses would probably deform the smaller grains as well as the larger, because of incompetence of the aggregate. Close relationship of small untwinned marginal crystals about larger strained crystals of a soft mineral is indicative of deformational recrystallization. The origin of the same texture developed from hard minerals is questionable, as fragmentation might produce the same result.

The sphalerite grains of transitional type from Cherryfield, Maine, do not show recrystallization derivation from the larger grains. The examples illustrated in Figs. 2 and 3, where the small crystals are contained within the larger one, show recrystallization, but these did not contribute to the development of transitional or mylonitic textures. If the textures of the transitional band had been a result of sphalerite recrystallization, the blebs of chalcopyrite and pyrrhotite should have inherited their former crystallographic pattern. Had recrystallization of all the constituents occurred, the previously exsolved minerals should either have recrystallized in place, thus inheriting their exsolution pattern, or migrated to new centers of crystallization, which would have resulted in larger blebs. The interstitial blebs of chalcopyrite and pyrrhotite in the transitional type of sphalerite are the same size as exsolved blebs within original crystals, and have a completely random orientation with respect to each other. The texture of the transitional type, which grades into the mylonitic, shows evidence of deformational origin from larger grains without recrystallization. Rupture of former larger grains containing exsolved chalcopyrite and pyrrhotite released these constituents to their present interstitial occurrence within the transitional zone.

Recrystallization, which implies development of new grains through transfer of material from an unstable to a stable nucleus, should result in a cemented aggregate, dependent somewhat on the extent to which it has progressed. In the mylonitic sphalerite from Maine, the difficulties involved in getting an unpitted polished surface were extreme. The pits were of the order of the grain size. The transitional type polished better than the mylonitic, but not as well as the coarser. Thus, granulation without noticeable recrystallization is suggested because of the lack of cementing material in the fine-grained aggregate.

There is much evidence of the derivation of sphalerite in the fine-grained band from coarser-textured material by pulverization to a mylonite. The gradation from the transitional is suggestive. The parallelism of the aligned pyrite and quartz fragments to each other and to the band, the buttressing effect of larger quartz masses on the alignment of the fragments, the marginal fragmentation and undulatory strain of the large quartz crystals, and the uncemented granular nature of the fine-grained sphalerite itself, are indicative of the deformational origin of the band.

Adams and Bancroft have concluded that soft minerals yield to deformational stress by gliding and secondary twinning, and in the case of harder minerals, the deformation may be accompanied by granulation to a mylonite.[8] Waldschmidt has noted that sphalerite from the Coeur d'Alene District, Idaho, responded to differential pressure by mylonitization.[9] Newhouse and Flaherty[10] state that sphalerite from Rammelsberg, Germany has "a fine-grained equidimensional texture with polysynthetically twinned crystals." According to Uglow, the deformed ore from the Slocan District, B. C., shows a brecciation of the sphalerite within a matrix of sheared and recrystallized galena.[11] Buerger's

[8] Adams, D., and Bancroft, J. A.: On the Amount of Internal Friction Developed in Rocks during Deformation, etc. Jour. Geol., vol. 25, p. 637, 1917.

[9] Waldschmidt, W. A.: Deformation in Ores, Coeur d'Alene District, Idaho. ECON. GEOL., vol. 20, p. 584, 1925.

[10] *Op. cit.*, p. 615.

[11] Uglow, W. L.: Gneissic Galena Ore from the Slocan District, British Columbia. ECON. GEOL., vol. 12, p. 649, 1917.

experimental observations indicate that plastic deformation of sphalerite may be accompanied by fragmentation.[12] On the other hand, Schneiderhöhn shows a polysynthetically twinned sphalerite grain crossed by a zone of rupture in which recrystallization has begun.[13]

These observations suggest that sphalerite yields to differential stress by plastic deformation and granulation, and that deformational recrystallization of sphalerite is either rare or difficult to recognize.

Sphalerite from Cherryfield, Maine, manifests slight deformational recrystallization (Figs. 2 and 3), but the microscopic evidence (Figs. 2, 4, 5, and 6) obviously points to plastic deformation succeeded by fragmentation as responsible for the development of the transitional and mylonitic sphalerite from originally coarser material. Stress effects were least in the region occupied by the coarsest sphalerite and are evidenced by secondary twinning and bending and fracturing of lamellæ; they were greater where the transitional type has been developed by plastic deformation succeeded by rupture and granulation, and greatest in the mylonitic zone where the fragmented aggregate was pulverized to a mylonite and shearing effects caused pyrite and quartz fragments to be drawn out into aligned rows.

SPHALERITE FROM FRIEDENSVILLE, PENNSYLVANIA.

The primary ore at Friedensville occurs in small replacement veinlets and masses in the dolomitic limestone country rock, in large masses which are probably metasomatic, and as open-space fillings. The sphalerite in the ore is characterized by a variety of textural types. Pyrite is the other prominent sulphide mineral, occurring in varying proportions with sphalerite.

Country-Rock Veinlets.—The veinlets and small masses of sphalerite in the country rock are largely metasomatic replacements but have not inherited the texture of their host. The lime-

[12] Buerger, M. J.: The Plastic Deformation of Ore Minerals. Amer. Miner., vol. 13, p. 37, 1928.

[13] Schneiderhöhn, H., and Ramdohr, P.: Lehrbuch der Erzmikroskopie, Bd. II, p. 105. Berlin, 1931.

stone, which has been recrystallized in part, has fairly equidimensional grain size, with average diameters 0.02–0.1 mm. Replacement of this matrix by pyrite and sphalerite occurred, resulting in pyrite in sizable crystals, and sphalerite of variable grain size which is, moreover, considerably larger than the grain size of the limestone. Large grains of sphalerite are commonly seen which had metasomatically attacked several limestone grains. Pyrite has been replaced by sphalerite, and neither mineral shows evidence of deformation. The pyrite has not been fractured, nor has sphalerite been noticeably twinned.

Open-Space Fillings.—Filling of open spaces generally resulted in crystalline, somewhat banded ore, the bands due to repeated deposition of pyrite and sphalerite. The structure is mostly conformable to projections of country rock on which the minerals have been deposited. Sphalerite continued to form after pyrite ceased. Etching of the sphalerite brings out twinning and marginal granulation in some specimens, although others show little evidence of deformation.

Textures of Massive Ore.—The massive ore is characterized by several textural facies: namely, essentially undisturbed sphalerite; a deformed and partly granulated facies, in part semi-schistose, and frequently containing mylonitic zones; a homogeneous fine-grained mylonitic facies; and a recrystallized facies, with unfractured pyrite of peculiar habit apparently replaced by sphalerite in rosette structures.

Gradations are present from aggregates of slightly twinned but otherwise undeformed sphalerite crystals to highly deformed sphalerite masses, in which but few intensely twinned large grains remain between zones of mylonitized sphalerite containing fragmental pyrite.

Undeformed Facies.—The grain size of the undeformed massive sphalerite is variable, as in the wall-rock metasomatic veinlets, and the associated pyrite had euhedral habit before replacement by sphalerite. Within several of the larger grains of this type of sphalerite, blebs of chalcopyrite have been observed. Although apparently localized along crystallographic directions, they are too few and small to enable an exsolution origin to be

proven. However, the writer believes that these chalcopyrite blebs have been unmixed from a pre-existing solid solution of copper-iron-sulphur-rich sphalerites. Fig. 7 shows the variable grain size of the massive sphalerite, and although some of the grains have been polysynthetically twinned, deformation has not been intense enough to produce granulation. This facies represents original deposition.

Deformed Facies.—Considerable deformation is noted in Fig. 8, where etching has brought out an undulatory strain effect across the bent twin lamellæ of a single sphalerite grain. The sphalerite grain is surrounded by a multitude of finer grains of variable size; the large crystal and the surrounding smaller grains are similar to the mortar structures developed from strained quartz. Close examination shows new grain growth in the lower corner of the large sphalerite grain similar to the grain growth shown in Figs. 2 and 3. Fragmentation of grain margins has been responsible for the texture of the finer-grained matrix.

The deformation shown in Fig. 8 can be traced to the more intensely deformed sphalerite of Fig. 9, in which zones of mylonitic sphalerite and fragmental pyrite contain large, highly deformed sphalerite crystals. In places, this phase of the deformation has resulted in parallel orientation of twin lamellæ which appears as schistosity, but the typical appearance is exemplified in Fig. 9. The lower portion of the photograph shows mylonitic bands, the central portion shows an intermediate stage in the formation of mylonitic material, and the upper part contains polysynthetically twinned sphalerite with curved lamellæ. This facies is an intermediate stage in the formation of mylonitic sphalerite from original coarser textures.

Mylonitic Facies.—The typical mylonite, which appears cherty in the hand specimen, is shown in Fig. 11. The remarkably even texture has been brought out by etching, which shows an average grain size of about 0.01 mm. although many grains are as small as 0.002 mm. diameter. Crossing the specimens of mylonitic sphalerite are numerous veinlike segregations of lighter-colored sphalerite, in which the sphalerite grain size is larger. One of

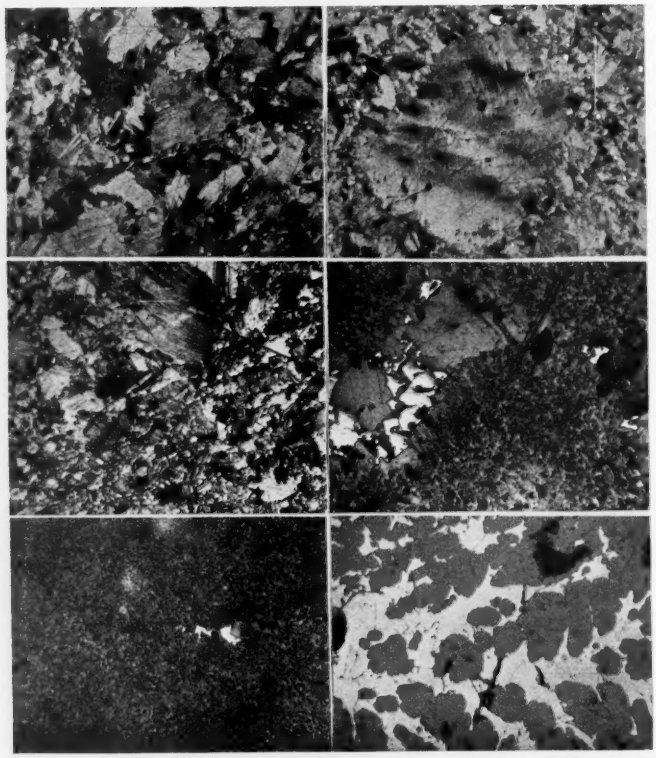

FIG. 7. Original textures of massive sphalerite. The grains are variable in size and have been twinned, but there is no perceptible granulation of margins; *q*—quartz. Friedensville, Pa. Etched, reflected light. × 60.

FIG. 8. Undulatory strain effects crossing twin lamellæ of a single sphalerite grain, which is surrounded by smaller sphalerites resulting from marginal fragmentation. Pyrite fragments (white) are present in small amount. In the lower corner of the large grain, probable recrystallization has occurred. Friedensville, Pa. Etched, reflected light. × 60.

FIG. 9. Sphalerite and fragmental pyrite (white) showing deformation. Upper part shows bent twin lamellæ of a twinned crystal, central part shows twinned sphalerite grains of intermediate size and fragmental

these segregations is seen in the center of Fig. 11. Pyrite, although not present in the mylonitic material, is localized fairly abundantly in the segregations.

A portion of another segregation is shown in Fig. 10. A faint suggestion of a directional effect may be observed in the mylonite normal to the segregation, near the center of the photograph. This is thought to be incipient recrystallization. The large pyrite grain was formed earlier than the light-colored sphalerite of the segregation. The sequence was: (1) mylonitic sphalerite, (2) pyrite and (3) light-colored sphalerite of the segregation. The segregation presumably represents a solution channelway.

Origin of Mylonitic Sphalerite.—The dolomitic limestone from which this mylonitic material is said to have inherited its texture [14] has, where observed, an average grain size ranging from 0.02 to 0.1 mm. The variability was caused in part by recrystallization which preceded the emplacement of the ore.[15] This resulted, however, in the development of larger carbonate grains which, in turn, were metasomatically replaced by sphalerite of variable grain size, as discussed previously. The well-defined sequence in these wall-rock veinlets of pyrite followed by sphalerite is in contrast to that

pyrite, and lower part, narrow zones of mylonitic sphalerite. Friedensville, Pa. Etched, reflected light. × 60.

FIG. 10. Segregated veinlet of coarser sphalerite within mylonitic sphalerite. Recrystallization has produced the coarser sphalerite of the segregation after pyrite (white) formed. Directional effect of incipient recrystallization is apparent normal to the veinlet. Friedensville, Pa. Etched, reflected light. × 60.

FIG. 11. Mylonitic sphalerite, showing the uniformly fine-grained texture. Pyrite (white) is localized in the narrow segregation of coarser sphalerite (center). Friedensville, Pa. Etched, reflected light. × 25.

FIG. 12. Massive sphalerite (gray) which has replaced pyrite (white) in rosette structures. The curious relations are thought to be a result of complete recrystallization of a mylonite. Friedensville, Pa. Reflected light. × 25.

[14] Miller, B. L.: *Op. cit.*, p. 71.

[15] Fraser, D. M.: Microscopic Investigation of the Friedensville Zinc Ore. Paper presented at the forty-seventh annual meeting of the Geological Society of America, Rochester, N. Y.; Dec. 28, 1934.

found in the mylonitic material. A principal evidence against inheritance of texture is the larger grain size of limestone contrasted to the uniformly smaller grain size of mylonitic sphalerite.

Deformation produced the mylonitic facies from non-homogeneous coarser sphalerite. Beginnings of deformation are shown in Fig. 8, and considerable development of new textures by deformation is manifested in Fig. 9. In the region of greatest stress effects, pulverization of sphalerite resulted in the homogeneous, fine-grained mylonite. The textures of the various stages in the deformation are comparable to those shown by the sphalerite of Cherryfield, Maine, where the development of the mylonite can be traced from original coarser sphalerite.

Of mylonites in general, Shand comments [16] that if deformation of a massive rock continues to the final stages " the boulders will be broken up more and more, . . . and it will be milled down to finer and finer grain, with development of heat, until the rock becomes compact and flinty . . . forming a flinty crush-rock." Thus the mylonitic sphalerite from Friedensville is in accord with the petrographical concept of the development and appearance of some mylonites.

In polishing the specimens of mylonite the ease with which grains were torn from the surface, leaving it pitted, suggests that the material is fragmental. Conversely, the recrystallized sphalerite in the segregations polished readily.

Recrystallization, aided by solutions, proceeded as indicated by the sphalerite segregations. It occurred, probably without solutions, to the small extent indicated for the specimen containing the undulatory-strained grain, but it is not thought that deformational recrystallization of strained grains contributed appreciably to the development of the mylonite. Granulation was the dominant cause of the uniform texture.

Recrystallized Facies.—Certain specimens show relations which are quite different from those previously described. Fig. 12 shows pyrite subject to attack by rosette-structured sphalerite. Minute structures indicate that sphalerite continued to form after

[16] Shand, S. J.: The Study of Rocks, p. 197. London, 1931.

pyrite crystallization was complete, yet the gross relations seem to suggest that the pyrite dendritically threaded its way through a pre-existing mineral. Etching of the sphalerite grains shows them to be small to moderate in size and somewhat twinned. No distortion or granulation is indicated. The pyrite is not fractured.

The writer believes that the pyrite and sphalerite represented by Fig. 12 are essentially the same as the recrystallized pyrite and sphalerite of the veinlike segregations of Figs. 10 and 11. The difference lies in the magnitude of the effect. Pyritic sphalerite had been pulverized to a mylonite when, aided by solution activity, pyrite reformed and sphalerite recrystallized, and, overlapping pyrite recrystallization, attacked pyrite forming radial rosette structures within it.

The mylonitized material was unstable under prevailing conditions in that region, and recrystallization of all constituents occurred. The reworking of mylonitic sphalerite into segregations (Figs. 10 and 11) was probably accomplished by small amounts of residual solutions, and nothing indicates that the mass recrystallization (Fig. 12) could not have been effected by similar agents.

RESUMÉ.

Sphalerite, subjected to stress, may be plastically deformed, and if initial stresses are sufficiently great or continued, progressive fragmentation and rupture occur. Pulverization of the fragmented aggregate to a mylonite is the final result of the process. Deformational recrystallization of strained sphalerite to finer grain sizes is infrequent. If exsolution has occurred within larger grains, the liberation of the unmixed blebs to an interstitial, unoriented habit among smaller grains is probable evidence of disintegration. If recrystallization of strained and twinned crystals to smaller crystals is suspected, growth of related marginal grains to sizes larger than the individual lamellæ is indicative of recrystallization in certain cases.

The sphalerite from Cherryfield was subject to deforming stresses which produced typical deformed textures grading into a

zone of mylonite within the vein. Mylonitization was effected by stresses that caused plastic deformation to be followed by progressive fragmentation. Deformational recrystallization occurred sporadically, but did not cause the textural types.

Similar textures have been observed in the sphalerite from Friedensville, Pa. Microscopic evidences of deformation of the Friedensville deposit are numerous, and formation of the fine-grained cherty sphalerite is thought to have been caused by mylonitization. Evidence of inheritance of texture from the country rock is lacking. There was negligible deformational recrystallization but, aided by solvents, recrystallization of sphalerite has occurred in certain of the deformed facies, and a second generation of pyrite is associated with the recrystallized sphalerite. The paragenesis of the sulphide minerals is: (1) pyrite, (2) sphalerite; and where deformation occurred, (3) pyrite and (4) recrystallized sphalerite may be present.

ACKNOWLEDGMENTS.

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CAMBRIDGE, MASSACHUSETTS,
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RELATIONS OF LATER GABBRO TO SULPHIDES AT THE HORNE MINE, NORANDA, QUEBEC.[1]

G. G. SUFFEL.

SUMMARY.

Sulphide ores at the Horne Mine are indisputably later than all formations except, possibly, the later gabbro dikes. The relative age of these dikes has been much discussed, but most recorded opinion has been in favor of placing the dike intrusions later than all or part of the sulphide replacement. More recent statements have been non-committal but argue for entirely pre-sulphide dikes. In this paper, supporting other writers, the author shows that all chalcopyrite is post-dike beyond any reasonable doubt, being definitely later than post-diabase faults and veins. That the dike is earlier than all the pyrrhotite and pyrite, which as a rule form part of the same ore bodies, is less subject to proof, but it is shown that this is the most rational interpretation and the facts do not demand any other. It may be concluded that the entire sulphide mineralization is later than any of the local intrusives until factual evidence to the contrary can be presented.

INTRODUCTION.

One of the most outstanding features of the Horne geology is the presence of two persistent and prominent diabase dikes (the later gabbro), known locally as the north-south dike and the east-west dike. They are two of several in the region which are remarkable for their continuity, uniformity, and characteristically chilled edges. The north-south dike cuts directly through the surface ore-zone at the Horne and through the east end of the great " H " ore body on several levels. The east-west dike, very similar in most respects, cuts the north-south one almost at right angles but entirely south of the ore bodies except on a few of the uppermost levels.

These dikes are definitely later than any of the rock types recognised at the Horne mine except the sulphides. With respect

[1] Published with the permission of the General Manager, Noranda Mines Ltd., Noranda, Que.

to these, however, there has been and still is considerable difference of opinion. This paper presents previously undescribed evidence for the pre-sulphide age of the dikes.

FORMER VIEWS.

The Horne dikes have already been discussed by various writers, several of whom have placed their age later than the main sulphide mineralization. However, L. C. Graton, in a private report in 1929, presented convincing arguments for the pre-sulphide intrusion of the dike. Peale [2] admitted that pyrite and pyrrhotite as well as chalcopyrite had replaced the dike but thought this due to a rejuvenating effect during the last stages of mineralization caused by the intrusion of the north-south dike. In 1931, Cooke, James, and Mawdsley [3] stated their belief that the dike was intruded after the pyrite and pyrrhotite but before the chalcopyrite. Bruce,[4] in 1933, found it difficult to picture conditions which would favor this sequence and thought it possible to assume only one period of ore deposition, and that later than the intrusion of the dike. In 1934, Price [5] summarized the situation; he effectually refuted some of the main arguments for pre-dike mineralization, yet believed the evidence to date was not conclusive. Lindgren, in the latest edition of his "Mineral Deposits," states that the dikes are "probably later than the ore."

Although few will deny that there is post-dike chalcopyrite mineralization, there are some who are skeptical as to the con-

[2] Peale, Rodgers: Some Ore Deposits of the Rouyn District, Northwestern Quebec, Canada. A thesis submitted to the Division of Geology, Harvard University, pp. 114–125. May, 1930.

[3] Cooke, H. C., James, W. F., and Mawdsley, J. B.: Geology and Ore Deposits of Rouyn-Harricanaw Region, Quebec. Canada Geol. Surv., Mem. 166, 1931.

[4] Bruce, E. L.: Mineral Deposits of the Canadian Shield, pp. 203–205, 1933.

[5] Price, Peter: The Geology and Ore Deposits of the Horne Mine, Noranda, Quebec. Can. Inst. Min. and Met. Bull. 263, pp. 138–140. March, 1934. Good evidence is given for the lack of actual "pairing" or correspondence of ore bodies on either side of the dike. To the writer this has never seemed a particularly valid argument at best. Since there apparently has been no appreciable faulting on the locus of the dike and the dike crosses all structures at a fairly high angle, similar or identical rock types may be found on opposite sides and should be equally subject to replacement.

clusion that the entire sulphide mineralization is post-diabase, perhaps, for one reason, because this implies a long time interval between the granitic intrusion and metallization. Also, by inference, the origin and age of the numerous gold deposits of the surrounding area would become much less certain, especially should these dikes eventually appear to be post-Cobalt, as is definitely known in the case of two similar ones in the district. It must be acknowledged, too, that on superficial examination, except in a very few places, the dikes have every indication of being post-ore, sharp, fresh, chilled edges being in direct contact with massive sulphides.

EVIDENCE AVAILABLE.

Good contacts of the east-west dike with sulphides have not been available in the last few years, but what is known does not conflict with the evidence observed by the writer in connection with the north-south dike, to which this paper will be largely confined.[6]

Development has exposed contacts of the north-south dike with sulphides on each level except the seventh, down to and including the tenth. From there to the twenty-fifth level, the only occurrence known is on the seventeenth. Exposures on the first five levels have been in small ore bodies which, for the most part, were rendered inaccessible or unsuitable for study during the first years of mining. That these showed post-diabase chalcopyrite mineralization is revealed by earlier reports.

Since 1929, the writer has observed practically all new evidence that has been disclosed in development work. Although this has been meager, it is believed that a convincing case may now be presented for a wholly post-dike mineralization. Since observing the undoubted replacement of the chilled contact by sulphides (*C* ore body, 6th level, April 1931) and the apparent invasion of the dike by a flat vein-like sulphide mass of almost mineable size (404 stope, May, 1931), the writer has been persuaded that

[6] Recently this dike has been cut in several places within "C" ore body. As first observed by A. L. Dempster, pre-sulphide faults are shown, as well as other features entirely confirming the evidence obtained elsewhere.

the arguments against post-dike mineralization call for circumstances and processes that are too fortuitous and artificial to be seriously considered. When the juncture of the north wall of Lower "H" ore body and the north-south dike was intersected by a drift on the 17th level (Feb., 1932) evidence was obtained which was, to the writer, finally convincing.

Some skepticism with regard to this occurrence, and the continued reluctance of several to commit themselves with regard to these age relationships, led the writer to examine this occurrence again in minute detail. The results were most gratifying and constitute strong evidence in favor of the post-dike theory.

In this paper the writer does not propose to review former discussions and theories, nor all of the evidence that he has observed, but will describe the features of this critical contact in detail. Of the arguments opposed to the post-dike theory, only those which do not appear to be refuted by the facts will be considered. It should be made clear, however, that this occurrence is regarded as representing the *actual* dike relations in all parts of the mine. The combination of circumstances which give an opportunity to study these contacts does not occur frequently, and it is usual to find only the typical chilled edge, possibly carrying minute specks of sulphides, in sharp contact with massive sulphides or well mineralized rhyolite.

The North-South Dike.—The north-south dike is a quartz-augite diabase, averaging about 80 feet wide; it strikes north, and dips steeply to the east. It cuts all the formations and structures of the ore zone and persists practically unchanged in width and character to a depth of 2500 ft. which is the deepest developed level at present.

The rock has a characteristically chilled margin not found in any other intrusives of the region. The extreme edge is typically a brownish glassy selvage about $\frac{1}{8}$" wide. This carries microphenocrysts and weathers to a typical black raised rim one-quarter inch thick, with white specks. Inside of this, as a rule, there is about a foot or less of fine-grained, black, lustrous, fractured and broken material. At 5 to 8 feet from the contact the dike is

moderately coarse-grained, as it is at its center. Vertical shearing parallel to the contact is characteristic but is not ordinarily found more than 5 to 10 feet inside the chilled edge. More or less horizontal veining is also rather common, mostly as fine veinlets near the contact but also up to 3 inches wide (Fig. 1) and

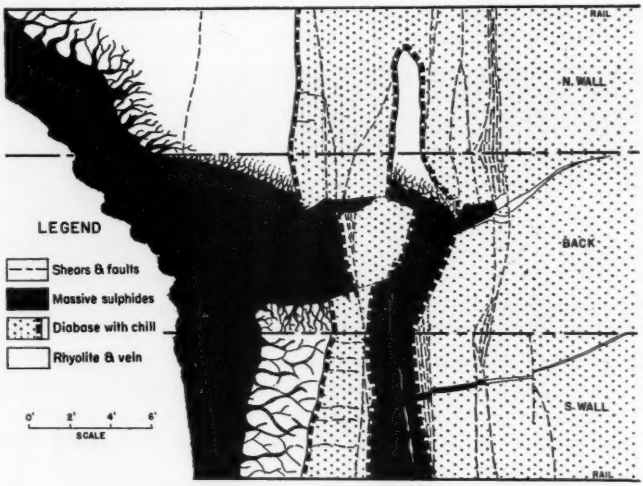

FIG. 1. Developed section of 17–12 drive, showing detail of rhyolite-diabase-sulphide contacts, including pre-sulphide faults.

possibly much larger. These may also occur through the entire dike. On the 17th level, they consist of fine-grained quartz, fine granular white calcite, epidote, chlorite, and a fine-grained red siliceous material, in varying proportions, commonly carrying a little pyrite and chalcopyrite.

Dike-Sulphide Relations.—The fact that the ordinary juncture of the dike with the huge massive sulphide ore bodies shows an unreplaced knife-edge contact with its chilled edge intact has been one of the prime arguments against the dike being pre-ore. However, it was recognized long ago that in certain places, the chilled

edge had been penetrated by seams and tongues of chalcopyrite, and close examination revealed specks of sulphides.

The occurrence on the seventeenth level presents practically all the characteristics of the sulphide-diabase contacts which have been observed elsewhere in the mine. Some, it is true, are in miniature but are none the less plain and significant. These are tabulated below and, for the most part, may be seen in Fig. 1.

FIG. 2. Composite reversed photograph showing back of 17–12 drive in plan as in Fig. 1.

1. The glassy typical chilled edge of the dike is in sharp contact with massive sulphides, but also,

2. A fretted replaced chilled edge is seen, where fractured, with tiny tongues of chalcopyrite penetrating it.

3. Post-diabase faults at right angles to the chilled edges have actually dislocated a block of a parallel offshoot about three feet thick, the same process apparently having wedged a small block of rhyolite, now replaced, into the wall of the main dike.

4. The faults have been replaced by massive sulphides, and have become obliterated where rhyolite was on one or both sides. The fault shearing is plainly visible where the diabase blocks touch, although mineralized slightly.

5. The sulphides show faint but definite banding in an east-west direction parallel to the unchilled diabase along the replaced north fault.

6. The sulphides show absolutely undisturbed contacts with the replaced unchilled diabase, with no trace of post-sulphide movement or rearrangement.

7. A post-diabase veinlet penetrates the dike for nearly 15 feet, tapering out to a mere thread. This veinlet is largely replaced by sulphide for a distance of 3 feet into the diabase, where the sulphides practically stop against a small pre-mineralization fault.

8. The typical chilled edge of the diabase has identically the same width and character in contact with rhyolite and sulphides.

9. The replacement contact with the rhyolite appears to have been controlled by faulting closely related to that which displaced the wedge in the dike. All traces of the faulting are replaced, however, as far away as can be seen (14 ft.).

10. Mineralized flat ladder veinlets occur in the offshoot. Some run completely through.

The sulphide material appears to the eye to be practically massive chalcopyrite. However, considerable pyrite is present and polished specimens, all taken east of the outer chilled edge of the offshoot, show chalcopyrite, pyrrhotite, pyrite and probably magnetite, with apparently the same paragenesis found commonly throughout the mine. Pyrrhotite is in microscopic grains but is not scarce. Pyrite is negligible in some spots, in others it is common.

The vein shown in Fig. 1 consists of fine-grained quartz and carbonate, much chlorite and later chalcopyrite, with a little pyrite. The vein is not banded.

No Two Periods of Mineralization.—It will be realized from the evidence presented above (which in no way conflicts with that to be found above the tenth level) that there is no possibility of all the sulphides being pre-dike. There remains then the argument that mineralization has taken place at two periods separated by the intrusion of the dike (used primarily to account for the scarcity of pyrite and pyrrhotite replacing the dike). This may have occurred (*a*) as a period of primary mineralization, largely chalcopyrite, following a previous one largely of pyrite and pyrrhotite, or (*b*) as an extensive post-dike rearrangement of earlier

sulphides, for which, however, no other cause can be imagined than the intrusion of the dike itself.

Against the first possibility, in addition to the fact that there are said to be few, if any, recognized examples in geologic literature, Price,[7] in his thorough study of the relationships of the various sulphides of the different ore bodies, has found no evidence of any profound gap between the pyrite-pyrrhotite and the chalcopyrite. Even if two separate periods of mineralization could be demonstrated, there would still be no proof that the dike was intruded between them since, as will be shown later, the apparent dominance of chalcopyrite next and within the dike demands no such explanation.

With regard to the second possibility, any rearrangement must have included extensive changes involving solution, transportation, and redeposition, with rather extensive replacement, which were more than local along the dike margin, as there is no evidence of reworked zones or changes of any sort in the mineralization which can conceivably be related to the dike. In fact, the whole mineralization pattern (especially on the lower levels, where this has been well studied) is entirely independent of the dike. Peale's theory that the heat of the dike, intruded in the last stages of mineralization, caused a subsequent and final wave of chalcopyrite replacement with some pyrrhotite and pyrite, now seems to have no authentic arguments in its favor and likewise to be an unnecessary assumption.

Dominance of Chalcopyrite Explained.—On the 17th level, the contact described occurs near one tip of a crescentic chalcopyrite zone lying along the south side and east end of the ore body, a zone which is typical of both the lower and upper parts of the "H" ore body, but has been particularly well defined from the 17th to the 21st levels. Fig. 3 shows that with the dike grazing the east end of the "H" ore body, and thus lying in a rich chalcopyrite zone which, however, shows no symmetrical relation to it, the dominance of chalcopyrite adjacent to and replacing the dike

[7] *Op. cit.*, p. 140. A gap between pyrite and pyrrhotite is said to be more probable, but the intrusion of the dike here would not explain the lack of pyrrhotite in it.

should demand no special explanation. A similar or comparable relation obtains on the 10th, 9th, and 8th levels, and also on the 7th, although here the contacts are masked by unreplaced metadiabase. On the 6th level, the chalcopyrite zone does not quite reach the dike; on the 5th, the nearest sulphides are very low in copper but the dike has metadiabase on both walls. Above this the contacts, if any, have not been revealed by development.

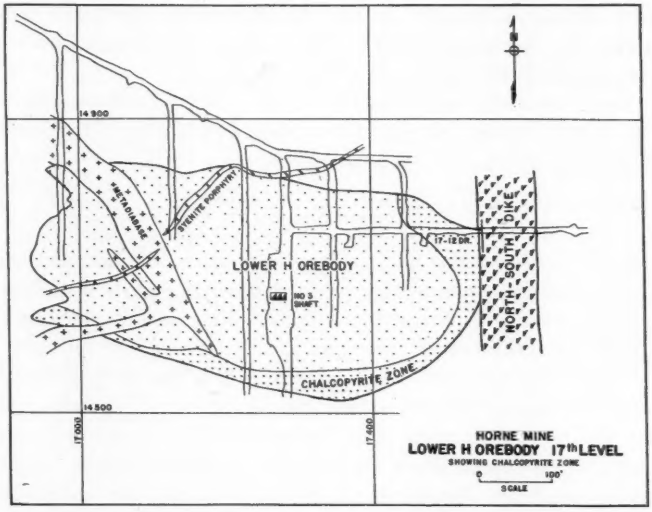

FIG. 3. Plan of Lower H ore body on the 17th level, showing relation of the chalcopyrite zone to the north-south diabase dike.

The writer is not familiar with the contacts of other ore bodies on the upper levels, except those of the " C " ore body, mentioned elsewhere. From the writings of Cooke and others one gathers that chalcopyrite stringers penetrating the chilled edges were not uncommon. Most of these ore bodies were rich in chalcopyrite.

Even if this condition did not exist, minor changes of mineralization are commonly noted against the obviously pre-ore syenite and metadiabase dikes within the ore bodies. The occurrence of

masses of magnetite against and replacing metadiabase in the south end of the lower " H " ore body, and tongues of chalcopyrite within and along the syenite dikes in the center of the great pyrite zone of the same ore body, are well established examples. It would not be strange should the diabase have affected mineral deposition similarly, even in a pyrite or pyrrhotite zone, where the solutions were able to penetrate the glassy selvage. At least one case is known (the east-west dike referred to by Price [8]) where later diabase is included in and cut by massive pyrrhotite and pyrite, and has chalcopyrite in places along the margin, and replacing small veins and faults within the dike.

Aside from all other explanations, it seems reasonable that a rock highly resistant to replacement should yield only to the latest or chalcopyrite phase of mineralization.

CONCLUSION.

It can be shown that chalcopyrite has replaced the later gabbro or diabase dikes where opportunity occurred and post-diabase faulting, veining or fracturing existed. This chalcopyrite is not a local mineralization of uncertain age or a late phase following the main ore deposition, but an integral part of the ore body itself or of the chalcopyrite zone in the case of the " H " ore body. It is ordinarily accompanied by a certain amount of pyrite and pyrrhotite. To explain the scarcity of the latter minerals in occurrences which are themselves rarely found, it has been supposed that the dikes were intruded between stages of mineralization. However, in nearly all instances of sulphide-dike contacts, the occurrence is in an ore body or a part of an ore body which is high in copper. In the few cases where this is not so, pyrite and pyrrhotite are known to have replaced or penetrated the diabase. Where the dikes are in sharp contact with massive sulphides showing no replacement, or with only small chalcopyrite stringers, reasonable explanations may be offered.

It is the writer's conclusion after a considerable period of observation that the diabase preceded the entire mineralization

[8] *Op. cit.*, p. 140.

at the Horne, resisting replacement in the same manner as did the metadiabase and syenite porphyry, but to a much greater degree. Both of the latter may be found within the massive sulphide ore bodies, in places, apparently unreplaced and unmineralized. Like the metadiabase, the dikes strongly resisted replacement due to their composition, but additional reasons for their impregnability were their freshness, glassy impervious chilled edges, vertical attitude, uniform width, and the lack of appreciable faulting that displaced the contacts.

To explain all the known facts it is unnecessary to postulate a pre-dike mineralization. On the contrary, such a hypothesis must rest on rather vague suppositions and possibilities.

ACKNOWLEDGMENTS.

The writer wishes to thank Mr. H. L. Roscoe, General Manager of the Horne Mine, for permission to publish this paper, and the management in general for facilities used in its preparation. For a critical reading of the paper, he is grateful to Dr. M. E. Wilson, Geological Survey of Canada.

NORANDA MINES LTD.,
NORANDA, QUEBEC,
April 9, 1935.

AN INEXPENSIVE ROCK-SLICING MACHINE.

B. M. SHAUB.

DIAMOND saws for cutting minerals and rocks are usually expensive to purchase and not always satisfactory in operation. The one described herewith represents an inexpensive and efficient one devised by the writer.

Construction of the Apparatus.—A comparatively rigid frame, 12 × 24 inches (*A*, Fig. 1), was made by cutting 3 inch channel iron at 45° and welding at the corners with an oxyacetylene torch. To the top of the frame at one end a 7 × 12 inch piece of quarter-inch steel plate (*B*, Fig. 1), was attached with heavy countersunk machine screws for the support of a Delta compound feed (*C*, Fig. 1). The longitudinal and transverse feeds are calibrated to 1/1000 inch, much finer than needed, and provided with an azimuth circle. The retail price of this feed is $17.50.

The motor is a quarter-horsepower, repulsion induction type, and runs at 1725 R. P. M. Any good quarter-horsepower motor running around this speed will operate the saw satisfactorily and can be readily obtained at a nominal cost. The motor is mounted on a heavy block of hard wood so that the center of the saw arbor is level with the center of the clamp (*D*, Fig. 1).

The saw is attached to the motor shaft by using a grinding-stone arbor of the proper size and cutting off the extra length of threads.

The clamp for holding the specimens consists of pieces of cold-rolled steel bar of the size and proportions given in Fig. 3. This illustration gives all the information needed for constructing this device, which after thorough trial in cutting large and small pieces seems to have the correct proportions, strength and rigidity. The jaws of the clamp are compressed against the specimen by means of wing nuts. It is important to test the rigidity of the specimen before one starts the sawing, for the specimen, even though tightly compressed, may be supported on points which

act as pivots and allow it to partly rotate and twist or damage the specimen or saw.

A simple accessory, Fig. 2, for charging the disks consists of a casehardened tool steel roller 2¼ inches in diameter, 3/8 inch thick and provided with a 3/32 inch square groove in the center of the cylindrical surface. This groove provides a receptacle for the crushed bort and acts as a guide during the actual charging. The wheel is mounted on a No. 200 Fafnir ball bearing (obtain-

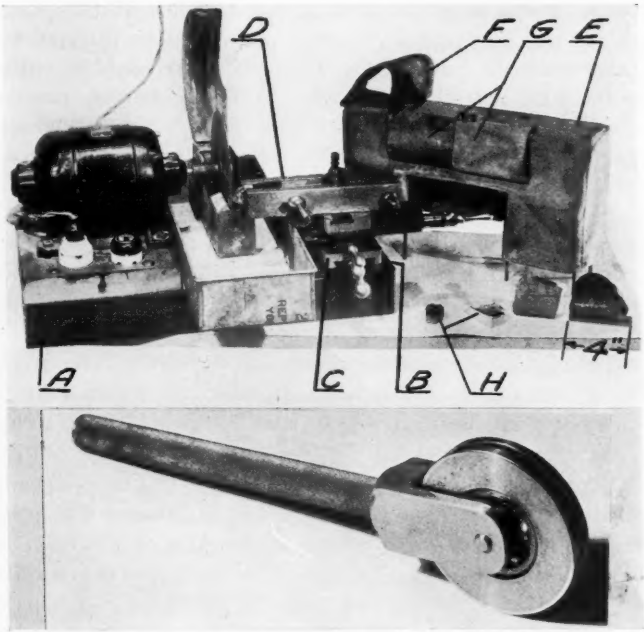

FIG. 1 (above). General view of apparatus, showing attachment of saw to motor, splash guard with top raised to show baffles, assembly of clamp attached to tool post of a Delta compound feed, spray hood with front and side flaps raised, some large specimens which have been cut, and smaller ones mounted to wooden blocks.

FIG. 2 (below). Charging roller, showing details of construction.

able at automobile accessory stores) attached to a handle by means of a yoke, as shown.

One of the convenient features of the outfit is the ease with which one may turn out new saws and true up old ones should they become damaged. To make a new cutting disk, a piece of sheet metal 8½ inches square is drilled in the center to fit the arbor. This must be done by clamping the sheet between pieces of wood, otherwise a ragged hole is likely to result. The corners are trimmed off with a hand metal-shears until the plate is essentially round or at least round enough to rotate with the motor without undue vibration. A *short* cutting tool properly ground is then set in the center of the clamp and securely held by setting up the wing nut with a wrench. While the roughly rounded blank is rotated by the motor the tool is *very slowly* advanced against the rotating blank until it is perfectly round or the desired diameter is reached. The best materials for disks are sheets of soft steel, hard rolled brass, hard rolled copper, spring phosphor bronze, and spring brass of 14 to 18 B. & S. gauge.

Crushed bort suitable for charging disks may be obtained from the Diamond Drill Carbon Co., or J. K. Smit & Sons, Inc., New York, at $1.50 to $2.50 per carat.

The cost of the material entering into the construction of the average saw of 8 to 8½ inches in diameter is less than a dollar. One carat of crushed bort will cut from 300 to 400 square inches of the average granite.

Charging the Disks with Crushed Bort.—The charging and recharging[1] of the disks is accomplished as follows: The powdered bort is mixed with vaseline, in the ratio of about one to four, in a small porcelain crucible and the mixture is then applied to the groove of the charging roller by means of a toothpick. The roller is held firmly against the disk while the latter is rotated ten to fifteen times by hand. If the material of the disk is too hard to allow it to take the proper amount of "set" by this operation, the disk can be rotated by the motor and the

[1] Vanderwilt, J. W.: A Simple Diamond Saw. ECON. GEOL., vol. 25, pp. 222–225, 1930.

charging wheel held against it with sufficient force to properly flatten the edge. This operation causes the charging wheel to rotate at about 6200 R. P. M., which is the chief reason for using a roller bearing. Too much set can easily be given by this method and the result is a rougher surface to the slice. This requires an extra amount of grinding before the chip can be mounted.

Splash Guard and Cooling Liquid.—It is important to provide an abundance of liquid to cool the saw and remove the rock cuttings, as they are very active in grinding the saw to a wedge shape and pulling out the diamond particles. Any appreciable wedging of the saw tends to cause binding and also to break the slices before the cut is complete.

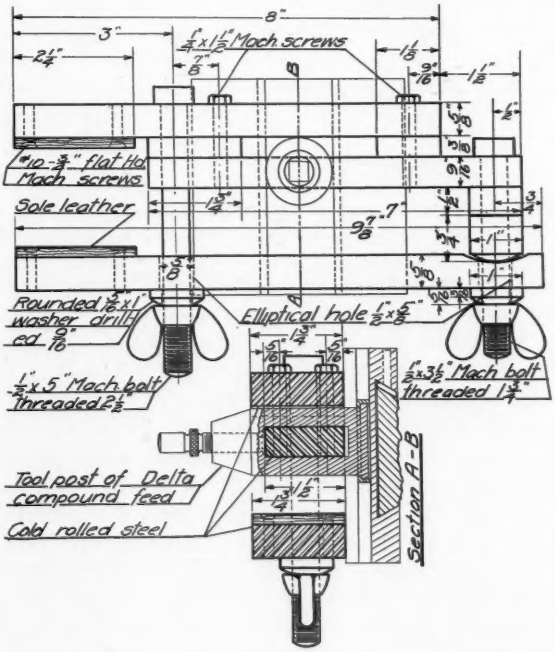

FIG. 3. Detailed assembly drawing of clamp, showing manner of attaching to tool post of a Delta compound feed.

The centrifugal force at the periphery of an 8-inch disk rotating at 1725 R. P. M. is sufficiently high to throw the cooling liquid with considerable force, and when it is captured by means of a splash guard (Fig. 4), the spray or mist is abundant enough

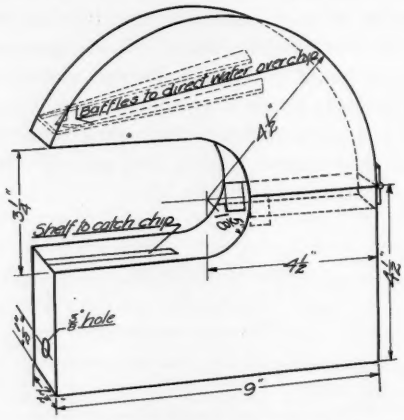

FIG. 4. Perspective drawing of splash guard, giving necessary dimensions.

to escape through the necessary openings and thoroughly wet the adjacent parts. To overcome this the splash guard was set inside a large galvanized tray, $7 \times 20 \times 3$ inches, and a canvas hood (*E*, Fig. 1) with flaps at the front and side (*F*, *G*, Fig. 1) was supported over the splash guard by means of a frame consisting of brass rods soldered together. The splash guard is provided in front with a 3/8 inch hole near the bottom which permits the cooling liquid to flow into it from the large tray. The level of the liquid should be from ¼ to ½ inch above the bottom of the saw when at rest. While the saw is rotating the centrifugal force carries the cooling liquid to the top of the guard, where baffles direct it to a point over the specimen where the cutting takes place, thus insuring a flood of liquid at the point of cutting which keeps the cut clear of rock dust and promotes easier, faster and smoother cutting.

For frequent use, a cooling liquid which will not corrode steel, copper, brass or bronze should be employed. The one used, consisting of one part water and two parts glycerine, can easily be removed from the specimen and chip. Evaporation leaves the solution richer in glycerine, and it should be diluted by addition of water. For occasional use, water alone may be used, as after use the metal parts can be wiped dry and coated with a heavy lubricating oil.

The fact that observation is more or less obscured by the hood, although one can see the specimen and saw from front and side, is of no particular disadvantage, for one can tell better how the cutting is progressing from the hum of the saw than by observation. If anything goes wrong it usually happens so quickly that one would be unable to act even though the vision were perfectly clear. Fortunately, with reasonable care, there is very little danger of losing a specimen or damaging a saw even when cutting small pieces.

Cutting Operation.—The average chip for easy cutting should be about an inch cube. A piece of this size can be very easily held in the clamp and is large enough to provide a good-sized slice for proper orientation on a glass slide. Specimens from this size up to and including hand specimens are usually easily and firmly held unless of a very irregular or rounded nature. Somewhat larger specimens, if not too round, may be easily held and cut by lifting the top part of the splash guard. If desirable, it is believed the proportions of the various parts could be changed to permit the cutting of considerably larger specimens.

Chips which are too thick for grinding, and too thin and irregular to be held in the clamp, can be cemented to rectangular blocks of hardwood (*H*, Fig. 1) by using a cement of equal parts of sealing wax and stick shellac. Both the chip and wood should be heated before the cementing operation and allowed to cool before cutting. The blocks are easily held by the clamp and the cut made as desired. Greater care should be taken with these mounts, for the chip may be torn from the block and damage the saw, but more likely the chip will be broken. No

trouble should be encountered if the saw is kept properly charged and the feed somewhat reduced. The chip is easily removed from the block by placing it on a medium hot plate.

The excess part of friable chips already mounted to an object glass with Canada balsam may be removed in a like manner by cementing a wooden block to the back of the slide with undercooked Canada balsam. The block may be removed without injury to the mount by placing it in water which is slightly uncomfortable to the hands.

Smooth round pieces, such as diamond drill cores, can be held in the clamp by using two pieces of soft wood with a V-shaped notch to hold the drill core.

Rate of Cutting and Character of Slices.—A quartz crystal having a cross-section area of 2.2 square inches was cut with a steel disk in 36 seconds, or at the rate of one square inch in 16½ seconds. This rate of cutting is probably near the maximum, for it requires about all the torque available from the quarter-horsepower motor. The consumption of diamond is also increased under these greatly stressed conditions.

The cut surfaces are very smooth, and comparatively little grinding is required before mounting. The thickness of the slice depends upon the character of the specimen. Solid materials have been cut less than ½ millimeter thick. These thin pieces are too delicate to handle during subsequent operations, but may be desirable for showing megascopic structures or internal structures of fossils.

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April 13, 1935.

DISCUSSION AND COMMUNICATIONS

THE ORIGIN OF CYANITE.

Sir:—In a discussion of the origin of cyanite in a recent number of this journal, Prof. Stuckey[1] states that: "Taber noted cyanite in the gold-bearing quartz veins of Central Virginia and concluded that it came from below as a residual material from a granite magma." This statement was never made by me although it was previously attributed to me by Miss Jonas,[2] who states: "It [cyanite] has been noted by Taber in the gold-bearing vein of the Young American mine, 1½ miles north of Lantana. He concludes that the kyanite, like the veins, is of magmatic origin and came from below as residual material from a granite magma."

At the Young American mine a crystal of cyanite was found extending from the wall rock into the vein quartz, and a brief description of the occurrence, together with a photograph, was published by me.[3] Elsewhere in the same area cyanite was noted in the metamorphosed wall rock near the veins and it was also found with tourmaline in pieces of vein quartz lying on the surface. In a list of vein minerals given on pages 211–212 of my report, it was suggested that the cyanite in vein quartz at the Young American mine was probably derived from altered inclusions of wall rock.

The cyanite schist which forms the crest of Willis Mountain was also described in my report (pp. 26–29). It was stated that the schist had been formed from argillaceous sediments under conditions of dynamic regional metamorphism, but that the loca-

[1] Stuckey, J. L.: Origin of Cyanite. ECON. GEOL., vol. 30, p. 448, 1935.

[2] Jonas, Anna I.: Geology of the Kyanite Belt of Virginia. Kyanite in Virginia. Va. Geol. Surv. Bull. 38, p. 14, 1932.

[3] Taber, Stephen: Geology of the Gold Belt in the James River Basin, Virginia. Va. Geol. Surv. Bull. 7, pp. 128–129, 1913.

tion, not far from large areas of intrusive granites, suggests that contact action may have been an influential factor in bringing about the alterations. Monadnocks similar to Willis Mountain are fairly common in the Piedmont belt of Virginia and the Carolinas, and at all of these localities that I have examined the occurrence and origin of the cyanite appears to be the same as at Willis Mountain.

It is not impossible that some cyanite may be entirely derived from igneous magmas, but I found no evidence of such an origin for the cyanite studied by me.

STEPHEN TABER.

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COLUMBIA, S. C.

DIFFERENTIATION IN TRAPS AND ORE DEPOSITION.

Sir: Two admirable recent papers[1] by T. M. Broderick and C. D. Hohl will be classics in the theories of volatile transfer. They suggest to my mind certain comments:

1. The work on the copper contents of flows may well be compared with that of A. W. Groves.[2] Broderick obtained a copper content from 0.002 to 0.038, with an average of 0.011; Groves obtained not less than 0.008 (in a granite), but his usual figures are also about 0.01 for "Greenstones." G. W. Coleman (Tufts College, Chemical dissertation No. 137) also deals with the same problem. In the Medford diabase he got 0.047 per cent, in Ononadaga 4–1411 (an ophite) 0.193, in Cape D'or (Triassic) (the same location as the specimens which Broderick quotes from Lund, but not the same flow) B–75—0.08, C–65—0.00, C–106—0.037. Coleman describes in his dissertation special studies in which he tried to determine whether the copper was native or sulphide.

2. He also includes a study of a diabase sill where again there is a concentration of iron toward the top. This should be com-

[1] ECON. GEOL., vol. 30, p. 301, May, 1935, and Geol. Soc. Amer. Bull., 46–4, pp. 503–558.

[2] Miner. Mag., vol. 24, no. 148, March, 1935, pp. 33–41.

pared with the results obtained by C. C. Moore in his study of the Hendre sill as reported in his presidential address[3] on the "Volume Composition of Rocks." In both cases the magnesia is concentrated toward the bottom, the lime and ferrous iron toward the center, and the total iron is also higher at the top than at the center.

Further, the analyses made for me by E. E. Ware of the nearly vertical Lighthouse Point dike[4] also show concentration of magnesia toward the center, but little or no concentration of the iron, although more in case of the ferrous iron.

Broderick's work is quite consistent with papers which indicate that the early olivine is more magnesian. This is the olivine that settles out.

3. The striking feature brought out by Broderick is that the iron is presumed to volatilize toward the top as iron chloride. I do not know why the copper should not follow, and there is a bare suggestion of it, since in the Greenstone, the seven analyses of the upper half give .017 Cu as against .01 for five of the lower half, and in the Kearsarge, the upper 37 feet yields 0.013 as against 0.01 for the remaining 127 feet.

4. A paper in the July Bulletin of the Geological Society of America[4a] shows the distribution of helium, thorium, and uranium in the same Kearsarge and Greenstone flows. With regard to the interesting doleritic streaks, which resemble a pegmatite in some respects and are called by Marvin light and dark types of diorite, I have seen exposures where there were flow lines that seem to me of the same nature, and the alternate streaks of diorite and ordinary aplite may be due to a streakiness in the distribution of volatiles due to a rather slow flow when the rock was already viscous.

When he says that I consider the copper as precipitated in permeable channels by the reducing action of the ferrous iron of the amygdaloids and conglomerates he hardly represents me, for in abbreviating he lumps my position and that of Pumpelly to-

[3] Proc. Liverpool Geol. Soc. 1902–3, vol. 9, pl. 17 and p. 279.

[4] Jour. Geol., vol. 12, p. 89, 1904.

[4a] Bull. Geol. Soc. of Amer., vol. 46, pp. 1101–1120.

gether. I consider the whole trap with its gases as the reducing agent, as appears from the following quotation [5] in which I have corrected a typographical slip in the chemical equation.

How, then, was the copper deposited? Experiments have shown that in an unequally heated solution of copper and other chlorides the copper will be deposited at the hotter end if the solution is kept alkaline. If, therefore, in such a case the copper solutions can find some rock which will tend to keep them from being oxidized, and at the same time remain alkaline, there is no reason why copper should not be deposited.

The reactions by which the copper was precipitated have been discussed by Fernekes.[6] It appears that an unequally heated chloride solution will tend to precipitate copper toward the hotter end, if the solution is kept alkaline. Both desert waters and lavas and rock powders generally are alkaline. Suppose their alkali be represented schematically:

$$2\begin{pmatrix}Na_2Si_4O_9\\CaSiO_3\end{pmatrix}+2CuCl_2+\begin{pmatrix}C\\2FeO\end{pmatrix}=Cu+2\begin{pmatrix}Na_2\\Ca\end{pmatrix}Cl_2+\begin{pmatrix}4SiO_2+CO_2\\SiO_2+Fe_2O_3\end{pmatrix}$$

The deposit of the oxygen by union with ferrous iron, as advocated by R. Pumpelly, no doubt occurs at times at the other pole of the solution, but I am now inclined to lay stress on the reducing carbon gases proved to exist in these lavas by R. T. Chamberlin,[7] and assumed for lavas generally by Brun.[8]

Calcium chloride [and calcite], into which the carbonates may have gone, are intimately associated with the copper. The silica of the above reaction appears in the abundant secondary quartz, and the sodium and calcium chloride are characteristic of the mine water.

Recent papers by R. J. Colony on a magnetite deposit in Puerto Rico, by F. Walker on Scotch basalts and crinanites, and by S. I. Tomkieff on "Differentiation in Basalt Lava, Island Magee, Co. Antrim," [9] all seem to show a tendency for the magnesia to settle in the olivine, but for the iron to remain in the residual magma, and perhaps rise.

[5] Bain, H. Foster: Types of Ore Deposits, pp. 136–137.
[6] Econ. Geol., vol. 2, no. 6, pp. 580–584, 1907.
[7] The Gases in Rocks. Carnegie Institution, 1908.
[8] Recherches sur l'Exhalaison volcanique (1911).
[9] Geol. Mag., vol. 7, p. 502.

Does the recent work by Broderick strengthen the suggestion of an epigenetic source of the copper in a hypothetical deep intrusion which may be figured as an extension of the Duluth Gabbro?

I notice that Ahlfeld of Göttingen does not find such a source necessary for the Corocoro deposits. Recent work of Wells on the Ph ratio of prehnite and laumontite does not favor it. Broderick's analyses confirm the presence of copper and sulphur in the fresh traps. I see no reason why the copper as well as iron should not be subject to "volatile transfer," and be concentrated here and there in concentratable quantity, even as the silica, which also occurs in the traps, is concentrated in pure quartz, although by different reactions. But this is another story, with which I hope to deal later.

ALFRED C. LANE.

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MEDFORD, MASS.

REVIEWS

Origin of the Copper Deposits of the Ducktown Type in the Southern Appalachian Region. By CLARENCE S. ROSS. U. S. Geol. Survey, Prof. Paper 179. Pp. 165; pls. 44, figs. 5. Washington, D. C. 1935.

The geologic features of a group of copper-bearing pyrrhotite veins of the Ducktown type, extending through the mountainous region from Virginia to Alabama, are described. Most of the veins follow the strike of the highly metamorphosed country rocks, but a few cut across it. They are characterized by abundant pyrrhotite, with smaller amounts of chalcopyrite and sphalerite, and a little galena. Pyrite may be abundant or almost absent. The chief gangue minerals are amphiboles, but quartz, calcite, biotite, and in some places plagioclase are abundant. Less common are garnets, epidote or zoisite, pyroxenes, spinels, talc, and chlorite. The veins are believed to have been derived from a differentiating magma, but no parent body to which they may be ascribed has been identified.

Throughout the region, the veins of this type contain almost identical ores and gangue minerals, have been formed by similar geologic processes, and the sequence of genetic events has been nearly the same.

The author states two main purposes of the investigation. The first is a study of the genetic history, which ". . . includes the later magma and the hydrothermal stages of mineral formation, which together constitute the later parts of the story of magmatic differentiation—that is, we have here a group of intermediate processes that appear to be transitional between those giving rise to typical igneous rocks and those that commonly result in ore deposits." The second object ". . . has been an attempt to make the maximum use of petrologic methods in connection with field studies in the investigation of an ore deposit."

Treatment along these lines by one having the qualifications of the author of this paper is bound to produce results of much geologic interest and importance. Not the least interesting feature is that an effort to advance the bounds of knowledge in the manner indicated necessarily entails excursions into fields that have been only partly explored. One must expect that his report or interpretation of what he has found will not agree in all respects with that of others who have similarly ventured. With most of Ross's conclusions the reviewer is in accord, and if a different interpretation of certain features is suggested, this should not be

construed as an attempt to point out errors, but as presenting other possibilities that might properly be taken into consideration in forming a judgment on these debatable matters.

One of the most interesting sections of the paper is that on the "Chemistry and physics of ore formation." In this are discussed many of the features that are stated to be a main object of the investigation.

Ross apparently leans rather strongly to the view that magmatic vapors and gases have not played much part in the transportation and deposition of ore and gangue minerals. He qualifies this in places by taking cognizance of possible ways by which they may come into the picture, but the general trend of the discussion is to minimize their importance. In developing the argument he has brought up the question of whether magmas pass through a critical region as they approach the end of their cooling and crystallization. Other geologists have discussed this topic in connection with ore deposition, and these discussions are commonly so presented that the reader is likely to get the impression that the conclusions regarding a critical state have an important bearing on the possibility of volatile transfer.

Ross accepts the view that a critical state of the magma probably does not exist. Although the contrary opinion has adherents, this conclusion seems best in accord with the evidence; nevertheless, its applicability to the problem is questionable.

Probably Niggli was the first to develop in rather convincing form the idea of a critical stage in the history of a cooling magma. This would imply that when the residual liquid reached this region, *all* of it passed without change of composition into a vapor phase, which possessed the characteristic property of vapors of tending to expand indefinitely. This view was accepted by many, but later Morey and others showed that there were strong objections. This, in turn, seems to have created an impression that in some way a minimum of importance of gases in magmatic processes is thereby indicated. Nothing of the sort is implied in this conclusion, and it would be unfortunate to have this idea gain general acceptance.

A similar misapprehension seems to be held by some with regard to critical pressures. Certain discussions of magmatic phenomena indicate a belief that if pressures applied to a vapor exceed the critical pressure, the vapor will be condensed to a liquid, even though the temperature is above the critical temperature. No support for this can be found in theory or experimental data. At the critical temperature, the corresponding pressure is the critical pressure, but if the critical temperature is exceeded, no amount of pressure will reduce a vapor to a liquid.

So far as we can see at present, the question of whether magmas pass through a critical region has so little direct or theoretical bearing on the

question of whether magmatic gases are important in ore formation, and critical phenomena have caused so much misunderstanding, that it might be better in most cases to leave them out of the discussion.

It seems to the reviewer that the rôle of gases may be most satisfactorily approached in another manner. Probably no geologist questions that volatile or potentially volatile constituents are present in magmas. Volcanic explosions and other phenomena demonstrate this. The tremendous violence sometimes apparent in these explosions demonstrates also the great magnitude of the force that tends to drive the volatiles out. This expulsive force exists not only in magma that comes up to the surface in volcanic conduits, but also, in like degree, in intrusive magmas that invade the upper portion of the lithosphere. In the latter case, rapidity of escape depends upon the facilities provided by roof and wall rocks. Relatively impervious rocks restrain free escape, but the same expulsive force is present and ready to act when opportunity is given, as by porous rocks or by discontinuities of any kind. This expulsion is not dependent on a critical condition of the magma, for volcanic explosions occur in freshly risen magma, in which no one would suggest that critical conditions have been approached. At this stage the magma consists mostly of a mixture of fused silicates, and in such a fusion the critical temperature is never attained, at least in the earth's outer crust. It is probably thousands of degrees higher than that prevailing.

These familiar observations are cited to show that magmas which are far from a possible critical temperature and which are not advanced in crystallization can and do expel gases and vapors with great force. If the roof over a body of injected magma is so tight that a large part of the dissolved volatiles is held in during subsequent crystallization, their concentration increases in the diminishing residual liquid, and their vapor pressure rises. Nevertheless, any magma with a content of volatiles that is quite usual exerts great vapor pressure at all stages of its history, from the period when it is wholly a fused liquid down to the time when it is approaching the condition of a hydrothermal solution; and if the roof is porous they are driven out. With these facts in mind, we have a basis for appraising the part that gases play. The question then becomes whether the escaping gases are in sufficient quantity and possess the necessary chemical properties to remove from the magma significant amounts of material. On this there may reasonably be differences of opinion. It is, in fact, one of the most important problems in igneous geology awaiting solution. It seems, however, that the case for the volatiles might be made much stronger than it appears in the form in which it is usually discussed or than it appears in Ross's treatment, and that objections that have been raised might easily be met.

Ross argues that ". . . if vein-forming materials were transported as a

vapor phase, those possessing similar volatilities should be segregated together, or the relative proportions of the various elements in the resultant mineral suite should show a definite relation to their volatility."

This is a favorite argument, but one is inclined to ask whether the same deductions should not apply, *mutatis mutandis,* to soluble materials deposited from a liquid solution, and what evidence there is that the requirement is met; and further to inquire whether volatility or solubility has much meaning in either case unless the physical and chemical environment is defined.

Ross goes on to say: "Titanium, whose chloride is highly volatile, is very sparse." It is true that titanium chloride, by itself, is highly volatile, but according to a general law, the vapor pressure of a substance in solution is lowered in proportion to the molar quantity of accompanying material. Since the amount of titanium in a magma is usually very small, the partial vapor pressure of its chloride will be low. Furthermore, the vapor of titanium chloride readily reacts with water vapor, and nothing can be stated in even the most general terms regarding the quantity that will be volatilized, unless the concentration of accompanying H_2O and HCl is specified.

Moreover, in any consideration of gaseous transfer, account should be taken of the important principle that when an inert gas separates from a solution, other substances of even the most minute vapor pressure are distilled into it as into a vacuum, and are swept away. Thus, the presence of inert gases effects the transportation and removal of substances of low vapor pressure.

There is some experimental evidence also that in addition to the *intrinsic* volatility of the chlorides and fluorides of mineral elements, highly heated and greatly compressed water vapor or gas is able to *take into solution* substances of low vapor pressure. Laboratory investigation of the subject of volatility, and the conditions on which it is dependent, carried out in the light of modern principles, is much needed. We are chiefly dependent upon geological observations. A number of geologists of high repute have made studies which indicate that important transfers of material in volatile form have been made from granitic magmas to limestones and other wall rocks at a stage when the magmas were actively invading the walls. Wall rock that has been metamorphosed and greatly changed in composition by this advance guard of emanations has been subsequently engulfed by the progressively intruding magma, and inclusions of it are now found at a distance from the contact. The observations seem to have been made with care. If they are well based, they furnish important evidence that transfer from the granites to the limestones was made by gases rather than by attenuated liquid residues. The basic material added to the walls has not the character of either the

granite itself or of the liquid residue, and in a magma hot enough to be actively invading its walls the stage of hydrothermal residues would not have been reached; the emanations could hardly have been other than gaseous.

Somewhat analogous observations indicate that certain ore deposits have been formed during the fusion period of plutonic bodies, and these carry similar implications regarding the agency of gases. Wherever definite evidences are found that material has been split off from a plutonic body and transferred to its walls during the early, high-temperature stage of invasion, we can hardly escape the conclusion that the transfer was made in a gaseous medium.

Under these conditions the evidence is probably least ambiguous, but the evolution of gases, and transport of material in volatile form, are not restricted to this stage. They continue at lower temperatures, and most ore deposits appear to have been derived from magmas at a somewhat later stage, after crystallization of the irruptive has progressed further, and has thus concentrated the volatiles and metallic elements in a diminished residue, and so increased their vapor pressure. The tendency for the gases to be expelled has thus been augmented and they are able to overcome a greater resistance in the wall rock. The emanations at this stage are still pneumatolytic, but with the progressive cooling of the irruptive and its surroundings, vaporous or gaseous emanations will not penetrate so far from the parent body. At decreasing distances they will be condensed to hydrothermal solutions. Thus, material that has been deposited originally from vapors will ultimately be exposed to a hydrothermal environment, which will transport and modify it in a manner comparable to what occurs in secondary enrichment when supergene processes are imposed upon hypogene.

The fact that many ore veins carry the imprint of hydrothermal action can hardly be regarded as evidence against the view that an important part of their material left the magma in volatile form. That one sort of geologic process has been active in producing results that we see is seldom sufficient to exclude other processes that may have acted successively or simultaneously. Probably many of the main and secondary phenomena in magmatic systems are the result of more than one process.

In several places Ross seems to accept the validity of the ideas expressed in the preceding discussion, as where he says: "The dominance of a liquid phase in certain stages of vein formation does not preclude the dominance of a vapor phase in other stages," and other passages of similar import might be quoted.

It is somewhat difficult to harmonize these remarks with the general trend of his discussion, or to gather from them how much importance he attaches to vapor transport. He is undoubtedly familiar with the

principles involved, but he does not seek to make specific application of them, and his arguments are opposed to the importance of this process. The impression is that he accepts the principles in the abstract and recognizes that they may have important application in certain types of ore deposits, but that his predilection is strong for the agency of liquids as chief factors. At the same time he is not so committed to this explanation but that he recognizes other possibilities.

In the process he favors he is in accord with many geologists. To others, the scarcity of evidence of transitions or direct connections between the aqueo-igneous residual liquids of the final magmatic stage (especially pegmatites) and the hydrothermal solutions to which processes of ore deposition are ascribed; the apparent necessity that magmatic vapors at high temperature should be expelled from intrusive bodies brought into a region where pore space or other avenues of escape are provided; together with a considerable amount of field evidence attesting results in accord with expectation, appeal as leading to a different conclusion. Here also, however, some of the links between magmatic vapors and ores have not been satisfactorily established. Neither group can assert with confidence that the available evidence is sufficient to prove with finality either mode of derivation from the magma. It is highly desirable that the two possibilities should be definitely recognized, and that field geologists should seek without bias to obtain evidence.

Ross gives an extended discussion of the "Criteria for the determination of mineral sequence," in order to lay a foundation for establishing the genetic history of the ore deposits. His treatment of this subject is admirable, and it might well be studied with care by many petrologists, who still are inclined to accept criteria for relative ages of minerals that have been shown to be unreliable or misleading. His statement deserves emphasis that:—"No problem that presents itself to the petrologist or student of ore deposits is of more fundamental importance than a correct interpretation of the genetic history of a mineral assemblage, such as a rock or ore body, and yet the criteria for determining mineral sequence have been very imperfectly evaluated."

A minor criticism might be made here of the manner in which Ross (and other geologists) have used the term "reaction series," in connection with processes that occur in migrating solutions. Reaction processes and the formation of reaction rims have been recognized for many years, as the natural result of chemical reactions between minerals and solutions in which they are unstable. To this subject Bowen made the important contribution of definitely recognizing and formulating a "reaction principle," according to which a mineral or assemblage of minerals precipitated at one stage of the crystallization of a magma becomes unstable in relation to the changed composition of the residual liquid of

the same magma at a later stage. The succession of minerals formed as a result he termed a "reaction series." The important feature of the process is that it takes place in a closed system—one in which no material is added or abstracted. To apply the same terms to reactions in an open system, though perhaps technically justifiable, is likely to obscure the special significance that they have in closed systems.

Ross finds that: "Study of the copper-bearing veins of the southern Appalachian region has shown that they have had a common genetic history. Essentially the same stages of development have been recognized in each deposit." The paragenetic succession of minerals has been studied in detail, and the relations are copiously illustrated by photomicrographs. A great variety of minerals is present, most of them preceding the sulphide stage of deposition, and many of them have a high-temperature aspect.

In these Appalachian veins, as in many other ore deposits, the presence of a large amount of ferromagnesian silicates presents a problem of considerable difficulty. Ross gives good reasons for believing that ". . . it is probable that the vein-forming solutions were all the result of the differentiation and crystallization of a single magma—that is, the aplite, pegmatite, quartz, ferromagnesian minerals, carbonates, sulphides, and volatile constituents were all derived from the same ultimate source, a single crystallizing magma." The difficulty in accounting for the high-temperature ferromagnesian minerals in ore deposits lies in the fact that processes of magmatic differentiation commonly cause the end-stage liquids to become more and more free of these constituents and more and more siliceous and feldspathic; and the problem is to develop from available evidence and general chemical principles a probable scheme that will restore to the vein-depositing medium (of whatever sort) the ferromagnesian constituents that residual liquids ordinarily lack. This presents difficulties of solution wherever high-temperature silicates are found as important constituents of ore deposits; in the veins of the Southern Appalachians it appears especially difficult in that many high-temperature silicates preceded calcite, whereas a small group of similar silicates was formed by the replacement of calcite after the carbonate stage. These last are diopside, tremolite, a little wollastonite, biotite, and possibly small amounts of talc and epidote.

In elucidation of the problem, Ross cites and discusses the well known work of Shannon on the diabase pegmatite at Goose Creek, Virginia. At this locality, the main body of diabase (dolerite) is cut by irregular dikes or veins of a coarse-grained pegmatite facies, which in places have nearly the same composition as the parent body, but elsewhere have been altered at a late stage by the removal of a large part of their ferromagnesian constituents and recrystallization of the remaining material. Ross

argues logically that the basic material thus abstracted was later deposited at some point away from the source, and he sees in this process an answer to the question of the derivation of the ferromagnesian minerals of the ore veins. Such occurrences are important evidence of derivation, but there still remains the question as to the kind of medium that effected transfer. In the metamorphosed pegmatite at Goose Creek the presence of B_2O_3, CO_2, S, F, and Cl is indicated by certain accompanying minerals. Ross believes that these volatiles performed their function while dissolved in a residual liquid. To the reviewer, who has studied this occurrence in the field and in the laboratory, the participation of a vapor phase is suggested by the phenomena; but it is doubtful if the relations at this locality are sufficiently significant in their implications to afford a test of either theory.

The merit of Ross's treatment of the matter, as applied to the Appalachian veins, is that it represents a well conceived attempt to trace the vein constituents to their ultimate source, and determine the chemical and physical conditions controlling the processes by which they were picked up, transported, and precipitated.

A complete answer to the question has elusive qualities, for mining operations, naturally, are not continued below the depths at which there are prospects of finding pay ore, and it is in the greater depths that the links directly connecting ore deposits with the magma are presumably to be found. There must be many occurrences, however, where important evidences as to the nature of "vein roots" have been laid bare by erosion, but these seem seldom to have been satisfactorily identified.

The participation of volatiles in one form or another in vein formation (and many metamorphic processes) is commonly accepted; there is less agreement as to whether they have acted while dissolved in a hydrothermal solution, or whether they have performed a great part of their function of transportation in a separate gaseous medium. Many fundamental problems relating to the nature and history of magmas are involved in this question.

An important feature of Ross's work is his conclusion regarding the significance of the abundant accompanying carbonates. He believes that: "The solution of the problem of the paragenesis of the pyrrhotite ore bodies of the Ducktown type in the southern Appalachian region depends very largely upon determination of the origin of the carbonates that are so abundant in many of them." Earlier work had led to the belief that the calcite, dolomite, and ankerite represent partly replaced limestone lenses at a fairly definite horizon in a sedimentary series. Ross finds, however, that ". . . when all the deposits are considered there is at least one and probably several mineralized zones in the early pre-Cambrian Carolina gneiss, three deposits in the Roan gneiss [a metamorphosed in-

trusive sill], and one or more zones in the Great Smoky conglomerate [which may be either Cambrian or pre-Cambrian]." Moreover, he finds that the Ore Knob vein cuts sharply across the beds of the Carolina gneiss, the Otto ore body appears to be a branching vein, and the Savannah vein, which strikes southeast in a country rock that strikes southwest, has been formed entirely by the replacement of schist and pegmatite. These relations and others seem to present clear evidence against the theory of replaced limestone lenses. Replacement of wall rocks has been a principal process, but the carbonates are simply members of the replacement group, and the CO_2 has presumably been derived from the parent magma.

This discussion has taken up only some of the outstanding features of the paper. The whole is stimulating and valuable, and should be carefully read.

C. N. FENNER.

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Geologic Structures. By BAILEY WILLIS AND ROBIN WILLIS. 3rd ed. rev. Pp. 544; figs. 202; pls. 12. McGraw-Hill Book Co., New York, 1934. Price, $4.00.

The new edition of Geologic Structures differs from earlier ones in many respects. Improvements are obvious. Rearrangement, condensation, additions of new material and literature render the book more useful for student and teacher. The 57 new illustrations, 27 of which are inserted in the chapter on practical problems, are welcome.

Textbook writing is difficult and frequently a thankless task; the author will never please everyone. Since the merits of this textbook are widely known and have often been mentioned, the reviewer feels that some adverse criticism may be in order, especially since a textbook is meant largely for the student who has not yet developed the ability of independent judgment and criticism.

Unfortunately, the book is neither well balanced nor complete. Structures typical of sediments (faults and folds) predominate, and metamorphic and igneous rocks are much neglected. Faulting is discussed very broadly in 121 pages, folding in 87 pages. Only 14 pages (and 15 literature references!) are devoted to metamorphic rocks. This chapter contains a number of rather general definitions and a much too brief treatment of rock flowage. The discussion of cleavage, schistosity, stretching, primary or secondary structures, shear folding, flow folding, ptygmatic folds, and faults in metamorphic rocks are missing or barely and very superficially touched. Modern authors like Sander, and the whole field of petrotectonics are not mentioned. One cannot help feeling that large areas of the earth's surface have been neglected. All new

methods which may help to solve the most intricate and difficult problems of structural geology should be included in a complete textbook on geologic structures.

The chapter on igneous rocks is greatly improved in the new edition, but large portions of this chapter are devoted to rather general and incomplete definitions of the form of igneous bodies, rather than their structure. The relation of igneous rocks to larger, major structures, is not mentioned.

From the length of these chapters the student must receive the impression that metamorphic and igneous rocks have no structures or are not worth attention.

The chapter headed "Field methods" deals largely with office methods and could be shortened considerably by elimination of repetition. Should not the student be told which structural elements he should observe in the field, and how? A suggestion as to how to take oriented samples is lacking. An example of a modern structure map and a selection of symbols as suggested by the U. S. Geological Survey would be helpful. Block diagrams, as one way of presenting intricate structures and their construction, should be discussed. A short outline of geophysical field methods and the detection of hidden structures would be valuable to the oil geologist. The appendix on experiments could be shortened. The plates were all published long ago and newer material ought to be used. Experiments by Daubrée, Paulke, Fath, Seidl, Mead, Riedel, Tokuda, and many others are worthy of mention.

The clearness of presentation could be improved by avoiding numerous repetitions and by more precision. The definition of a fault appears four times. Strike and dip are defined twice, and illustrations given. The chapter on mechanical principles is repeated in subsequent chapters and seems therefore unnecessary. A chapter on "Nomenclature of faults" (page 205) appears again on page 496. The "fact" that joints occur in two groups, as compression and tension joints, is repeated unnecessarily often, for instance twice in one paragraph on page 114. The definition of upthrusts is so vague and contradictory that the reviewer doubts its usefulness.

Faults are variously defined as follows: on page 218, "a fault is a plane of parting with appreciable displacement"; on page 142, "faults are of all lengths, from those that measure in miles, down to those that can be detected in finely crystalline rocks only with a high-power microscope"; on page 122, "this means that every visible joint is a plane of displacement, a fault of at least microscopic slip"; on page 19, "A fault is a break or shear on which there has been an observable displacement." The reviewer, despite a careful study of the book, fails to find a precise statement of the authors' concept.

The terms competent and incompetent structures are introduced with different genetic implications. On page 78, the direction of pressure determines the competency of a structure and on page 79, the strength of the beds enters the definition: "-up-arching can only occur when there are strong beds, competent strata, capable of lifting." The student may be at a loss to know whether it is the direction of pressure or the strength of the beds that determines competent or incompetent structures.

Another example of lack of clearness is the discussion and application of the stress and strain ellipsoid. The construction of the ellipsoid is possible only for one point of a system and not for a larger region which is inhomogeneous. In faulting, for instance, conditions change from point to point, as is clearly shown in the drag along a fault zone or plane. It is not permissible, therefore, to draw a larger diagram which embraces the fault plane as merely one of its shear planes, and a smaller one which shows the condition in the immediate neighborhood of the plane. Any plane of discontinuity, as, for instance, bedding or contacts, gives rise to different conditions. This is clearly shown in joints and shear planes, which occur at different angles in a brittle layer (a dike or sill) between other layers. The simultaneous use of the principle in both a microscopic and a regional sense, without a definite explanation of homogeneity, is impossible. This confusion is shown in Fig. 195. If MM' is the axis of elongation, tension joints cannot form as indicated in TT. If T is constructed on the basis of a smaller ellipsoid, showing the conditions nearer the fault, this should be indicated. Figures 7, 103, and 195 are not clear, and are objectionable for this reason.

"The forces which for so long had gradually raised one strip and depressed another were replaced or overpowered by intense compressive stresses, which acted horizontally and demonstrated their power by folding the strata that had accumulated." A statement like this is inclined to give a student the idea that everything is settled. The reviewer, however, would like to ask how much of this process we know? He suggests that it would have been very much better to have limited the discussion of the forces, because we know very little about them, and instead to have discussed more fully the movements and their traces which we can observe.

Several additional suggestions may be offered. The table of apparent dips in Appendix 1 would be presented better graphically, as is done by W. S. Tangier Smith. A graphic presentation of the properties of matter would help the student better than the vague description on page 417. In chapter XII, the insertion of a map like the beautiful Belcher Island sheet of the Canadian Geological Survey, or any modern areal map, would express more than words. The term "regional habit" is vague and should be explained. Figure 77 on page 170 is not clear and represents

an impossible situation. A discussion of the relation between joints and other structural elements, like axes of folding, linear stretching or flow, doming, etc. should be included in the chapter on jointing.

The literature citations in the book have been dealt with in a rather unfortunate manner. The authors obviously abbreviated titles, but why take away in one case and add in another? The reviewer believes that an author listed deserves the right of correct citation, that the student ought to be impressed with the necessity of referring to the literature correctly, and that it is inconvenient if titles cannot be found because they are not correctly given. More than one third of all the citations in the book deviate from the original.

On page 243 too much honor was done to the present reviewer. "Das Batholithenproblem" and "Zur Terminologie der Plutone" were written by his brother, Hans Cloos.

Since there are natural limits to the volume of a book, certain chapters should be condensed and shortened, and repetitions eliminated. The book is unfortunately much more schematical than necessary in a textbook. The student's interest should be stimulated and not subdued, he should be led to the urge for investigation of problems and not be confronted too extensively with accomplished facts.

In spite of the criticism, the reviewer recommends the book to his students for certain phases of structural geology. He realizes that we owe the authors a debt of gratitude. It is very much easier to criticize a good existing book, than to write a better one.

ERNST CLOOS.

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Grundwasser und Quellen Kunde. By K. KEILHACK. 3d ed. Pp. xi + 575, table, figs. 308. Gebrüder Borntraeger, Berlin, 1935.

The third edition of this well known work on ground-water hydrology which appeared recently, is, like the original edition, divided into three major divisions. The first, which deals with the sciences upon which ground-water hydrology is based, has not been changed materially. The second division, which treats of ground-water hydrology and its problems, has been enlarged. Additional data have been added to many chapters. Two new chapters by H. Reich and A. Ebert discuss geophysical methods as applied to the finding of ground water. Several methods are discussed but the resistivity method is described the most fully. A brief reference is made to the use of radioactivity methods. The third section, which discusses ground-water law, refers chiefly to Germany. An excellent bibliograpphy of 248 titles is a welcome innovation in the new edition.

GEORGE M. HALL.

Introduction to Geology. By E. B. BRANSON AND W. A. TARR. Pp. 470, figs. 456. McGraw-Hill, New York, 1935. Price, $3.75.

This is an elementary textbook of both physical and historical geology in which principles are stressed rather than technical data. It seeks to develop the subject in sequence. Part I starts with the elements, then considers minerals, next igneous activity and igneous rocks. This is followed by weathering processes, and the work of streams, ground water, and oceans, in producing materials for the formation of sedimentary rocks. Then follow sedimentary and metamorphic processes and rocks, and lastly, the work of snow and ice, wind, structural features, earthquakes. Part II follows the customary procedure of treatment of historical geology, in which technicalities and technical phraseology are held to a minimum. In fact, they are so minimized that the student is supplied with a rather thin veneer.

The book is well arranged. The many illustrations are carefully chosen and of good quality. It should prove highly satisfactory for a brief elementary course in geology.

BOOKS RECEIVED.

L. B. RILEY.

Montana: The Geological Story. D. E. WILLARD. Pp. 350, figs. 120. Privately published by author, Railway Building, St. Paul, Minn., 1935. Price, $2.50. First a popular non-technical description of the geologic processes that make landscapes; then interesting chats on many of the outstanding geological features of Montana in explanation of its scenery, its rocks, its rivers, its minerals; in part, a popular annotated guide for railway and highway routes. Simple, interesting, instructive; recommended for the traveler.

Geology of the Makaha Gold Belt, Mtoko District (So. Rhodesia). A. M. MACGREGOR. Pp. 47. So. Rhodesia Geol. Surv., Bull. 28. Salisbury, 1935. 1s 9d. Geol. map 1: 100,000: 185 sq. mi. Area also known as Kaiser Wilhelm gold belt. Lode mines of no great promise.

Annual Report, 1934, Tanganyika Geol. Surv., E. O. TEALE, Director. Pp. 61. Dar es Salaam, 1935. 2/50 s. Progress report of gold fields and general geologic fieldwork. List of publications and maps issued by department.

Annales du Service des Mines, Comité Spécial du Katanga, Tome V, 1934. Pp. 147, pls. 12. Bruxelles, 1935. 50 fr. L. DE LEENHEER: mindigite, a new hydroxide of cobalt; P. GROSEMANS: basic rocks, Tenke district; conglomerate, base of U. Kundelungu; A. JAMOTTE: Kakontwe limestone between Kengere and Muniafunshi; tourmaline-bearing eruptives of the Katanga tin district; P. VANDEN BRANDE:

genesis of gold-platinum deposit of Ruwe; A. DUPARQUE: coal of Lukuga and Luéna.

The Mineral Industry during 1934. Vol. 43. G. A. ROUSH, Editor. McGraw-Hill Book Co., New York, 1935.

Geologic Map of Klerksdorp-Ventersdorp Area. L. T. NEL. Geol. Surv. of South Africa. Pretoria, 1934. Two sheets in colors, scale 1: 60,000, covering 50 by 25 miles. Formations from Lower Witwatersrand to Karroo involved in a very complicated structure.

Geologic Map of Bethel Area (So. Africa). F. A. VENTER, A. W. RODGERS AND E. T. MELLOR. Geol. Surv. of South Africa, Sheet 51. Pretoria, 1934. In colors, scale 1: 148,752, covering 35 by 60 miles. Mostly Karroo; N.E. corner Transvaal system.

Barkerville Gold Belt, Cariboo District, B. C. G. HANSON. Pp. 42; maps 2, in colors, 1: 12,000, 14 sq. mi. Canada Geol. Surv. Memoir 181. Ottawa, 1935. 25 cts. Important gold pyrite veins and replacements in limestone. Structural control by wall-rocks emphasized.

Annuaire 1935, Comité d' Études minières pour la France d'outre-mer. Pp. 428. Paris, 1935. Complete list of administration, bureaus, societies and companies, mining laws and regulations, production and prices of metals and minerals for the French possessions, 1931–1934.

El Yeso en Lima, Perú. G. D. ZEVALLOS. Pp. 179, pls. 28. Cuerpo de Ing. de Minas del Perú, Bol. 110. Lima, 1934.

La Industria Minera en el Perú, 1932–33. J. HOHAGEN. Pp. 294. Cuerpo de Ing. de Minas del Perú, Bol. 111. Lima, 1935.

Geology of Southern Saskatchewan, Canada. F. J. FRASER, F. H. MCLEARN, L. S. RUSSELL, P. S. WARREN, R. T. D. WICKENDEN. Pp. 137, pls. 5. Canada Geol. Surv., Memoir 176. Ottawa, 1935. 50 cts. Map (folder) 1: 506,880, 62,400 sq. mi., showing Cretaceous-Tertiary formations, lignitic coal, clay, volcanic ash, also 13 E.–W. cross-sections. Occurrences of lignitic coals are described.

Lode Gold Deposits of Fairview Camp, Camp McKinney, and Vidette Lake Area, and the Dividend-Lakeview Property near Osoyoos, B. C. W. E. COCKFIELD. Pp. 38, maps 4. Canada Geol. Surv. Memoir 179. Ottawa, 1935. 25 cts. Brief descriptions of four separate areas.

Descriptions of Properties, Slocan Mining Camp, B. C., Canada. C. E. CAIRNES. Pp. 275. Canada Geol. Surv. Memoir 184. Ottawa, 1935. 75 cts. Supplementary to Memoir 173, in which the general and economic geology are discussed. Slocan Mining Camp includes three mining divisions: Slocan, Slocan City, and Ainsworth.

Nickel-Copper Occurrence in the Bushveld Igneous Complex West of the Pilandsbergen, Transvaal. C. M. SCHWELLNUS. Pp. 36. Geol. Surv. of So. Africa, Geol. Series Bull. 5. Pretoria, 1935. 6d. Deposit of norite type. Production expected in immediate future.

SCIENTIFIC NOTES AND NEWS

H. M. Kingsbury, after five years spent in studying the geology of the gold fields of New Guinea in the interests of Mining Trust, Ltd., London, is returning to America by way of Australia and the Orient.

H. Foster Bain, accompanied by Mrs. Bain, will sail for the Orient from San Francisco in December.

Philip Krieger, of Columbia University, recently returned from northern Mexico, where he has been investigating the silver and silver-gold areas.

Carroll H. Wegemann has been appointed regional geologist for the National Park Service, with a territory which includes the Great Plains and Rocky Mountain area.

E. K. Soper has joined the staff of the Geological Department of the University of California at Los Angeles.

D. F. Hewett, of the U. S. Geological Survey, succeeds G. F. Loughlin, now chief geologist, as geologist in charge of metalliferous deposits. He will continue to serve as the Survey's specialist on manganese.

A. I. Levorsen, chief geologist of Tide Water Oil Company, has resigned to take up personal practice at Tulsa, Oklahoma.

C. B. Jeppe, of Johannesburg, South Africa, has been visiting the United States and has now taken up work as a professor at the University of the Witwatersrand.

James L. Hall, who has been on the geological staff at Balatoc, is now resident engineer for Benguet Consolidated at the chromite properties in Zambales Province, P. I.

Loftus Hills, consulting geologist, is head of development work for companies operating on the Tavua gold field, Fiji Islands.

R. M. Overbeck and his wife have gone to the Philippines, where he is to examine mining properties for the International Mining Corporation.

Howard N. Lary, formerly geologist for the Empire Zinc Company at Gilman, Colorado, has been appointed R. F. C. examiner of small mines in Colorado, with office in Denver.

C. A. Bonine, head of the Department of Geology and Mining at Pennsylvania State College, and also of the Department of Petroleum and Natural Gas, has resigned the latter position and will be succeeded in it by William R. Chedsey.

Frederick G. Clapp, consulting geologist of New York City and Bronxville, N. Y., recently spent several weeks in inspecting producing and prospective oil areas in California and other parts of the Pacific Coast.

George H. Garrey now has his headquarters as consulting geologist and mining engineer at Room 1028, Patterson Building, Denver, Colorado.

Dorsey Hager has opened an office at 808 Olds Tower Building, Lansing, Michigan, as consulting mining engineer.

C. R. Forbes, of the Missouri School of Mines and Metallurgy, has returned there after three years spent in examination and operation of gold properties in California.

The National Research Council Committee on Grants-in-Aid will meet in March, 1936. Applications for grants must be filed with the Secretary of the Committee, Dr. Clarence J. West, by February 15. Additional information and application blanks will be furnished on request.

The Geological Society of America will hold its annual meeting on December 26–28 in New York City, with headquarters at the Waldorf-Astoria Hotel. The presidential address and smoker will be on December 26th, and the dinner on the 27th.

The Society of Economic Geologists will hold its Sixteenth Annual meeting in conjunction with the meetings of the Geological Society of America, on December 26–28, in New York City. Headquarters will be at the Waldorf-Astoria Hotel, and sessions will be held on December 26 and 27. Titles of papers should be sent to Professor W. H. Newhouse, Massachusetts Institute of Technology, Cambridge. The Society luncheon will be held on December 27 at the Waldorf-Astoria. Railroad certificates may be obtained from the Secretary, D. H. McLaughlin, Harvard University, Cambridge, Mass.

ECONOMIC GEOLOGY

Ten-Volume Index, Vols. 21–30, 1926–1935.

This Journal will publish in January, 1936, a comprehensive general index of the last ten volumes. This index will be invaluable to all libraries and users of the Journal, and in addition will constitute a general index covering much of the field of economic geology. The size will be about 150 pages. The price for advance orders is $1.60, for later orders $2.10.

Orders should be sent immediately to W. S. Bayley, University of Illinois, Urbana, Ill.

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